DESIGN OF A MARTIAN COMMUNICATION CONSTELLATION OF CUBESATS

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ABSTRACT

Design of a Martian Communication Constellation of CubeSats

Scott J Pirkle

Spacecraft operating on the Martian surface have used relay satellites as a means of improving communication capabilities, mainly in terms of bandwidth and availability. However, the spacecraft used to achieve this have been large spacecraft (1000s of kilograms) and were not designed with relay capability as the design priority. This thesis explores the possibility of using a CubeSat-based constellation as a communications network for spacecraft operating on the Martian surface. Brute-force techniques are employed to explore the design space of possible constellations. An analysis of constellation configurations that provide complete, continuous coverage of the Martian surface is presented. The stability of these constellations are analyzed, and recommendations are made for stable configurations and the orbital maintenance thereof. Link budget analysis is used to determine the communications capability of each constellation, and recommendations are made for sizing each communication element. The results of these three analyses are synthesized to create an architecture generation tool. This tool is used to identify mission architectures that suit a variety of mission requirements, and these architectures are presented. The primary recommended architecture utilizes 18 CubeSats in three orbital planes with six additional larger relay satellites to provide an average of over one terabit/sol downlink and 100 kbps uplink capability.

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LIST OF ACRONYMS

AU: Astronomical Unit

bps: Bits per second

COTS: Commercial Off-the-Shelf

DSN: Deep Space Network

DTE: Direct-to-Earth

EDSN: Edison Demonstration of Smallsat Networks

ISS: International Space Station

LEO: Low Earth Orbit

LOS: Line-of-Sight

MarCo: Mars Cube One

MAVEN: Mars Atmospheric Volatile Evolution

MC3: Martian Communications Constellation of CubeSats

MEPAG: Mars Exploration Program Analysis Group

MER: Mars Exploration Rover

MRO: Mars Reconnaissance Orbiter

MSL: Mars Science Laboratory

NODeS: Network and Operation Demonstration Mission

RAAN: Right Ascension of Ascending Node

RF: Radio Frequency

RKF78: Runge-Kutta Fehlberg $7^{th}/8^{th}$ order integrator

SKG: Strategic Knowledge Gap

SOI: Sphere of Influence

SWaP: Size, Weight, and Power

STK: Systems ToolKit

UHF: Ultra-High Frequency

WDP: Walker-Delta Pattern

Chapter 1

INTRODUCTION

1.1 Overview and Problem Statement

One of the defining characteristics of humankind is its desire for exploration and expansion. This desire, along with political tension [1], propelled humans to the surface of the moon in 1969 and plans exist to push humanity further into space in the future [2], [3]. According to their 2018 strategic plan, the United States' National Aeronautics and Space Administration (NASA) has a strategic goal to *"extend human presence deeper into space… for sustainable long-term exploration and utilization,"* [2]. Elon Musk's SpaceX has stated the company's desire to *"start launching humans to Mars in the mid-2020s,"* although this timeframe has been declared optimistic by some [3]. Regardless of specific launch dates, the desire among major space organizations to send humans to Mars is clearly demonstrated[3]; however, further investigation of Mars by scientific missions is necessary before manned missions can be undertaken [4]. In 2018, NASA's Mars Exploration Program Analysis Group (MEPAG) identified 33 strategic knowledge gaps (SKGs) that must be addressed by in-situ investigation before manned missions can be sent to Mars [4]. Several of the 12 high-priority SKGs require simultaneous multipoint measurements taken from the Martian surface, atmosphere, and orbit [4]. This need translates to a significant increase in the number of spacecraft operating in the Martian sphere of influence (SOI) in the near future, all of which will need to communicate with Earth.

Relay communications offer better performance compared to the direct-to-Earth (DTE) alternative [5] and relay operations have been carried out by large spacecraft (1000s of kg), such as Mars Odyssey [6], Mars Reconnaissance Orbiter (MRO) [7], and Mars Atmospheric Volatile Evolution (MAVEN) [8]. However, missions such as the 2018 Mars Cube One (MarCO) mission have demonstrated the feasibility of using CubeSats as an alternative for deep space networking [9]. This thesis analyzes possible architectures for a Martian Communications Constellation of CubeSats (MC3) to enable simultaneous multipoint measurements taken from the Martian surface. To be effective, the system will have to meet key requirements, listed below, which will be justified throughout Chapter 2. A further decomposition of these requirements is available in Appendix A.

1. The MC3 program shall provide at least 1 Tbits/sol (Martian day, equivalent to 24 hours, 39 minutes, and 35.244 seconds) average total downlink capability for the Martian system.
2. The MC3 program shall provide at least 1 kbps uplink capability for spacecraft operating on the Martian surface.
3. The MC3 program shall provide 99% continuous coverage of the Martian surface.
4. The MC3 program shall operate for a minimum of 10 years.

1.2 Motivation

Relay spacecraft have been used to increase the communications capabilities of Martian surface craft [6]–[8]. As shown in Figure 1, these craft have either communicated with Earth via a DTE link, shown in red, or via a relay satellite link, the two parts of which are shown in green and blue. The Mars Exploration Rovers (MER) [10], Mars Science Laboratory (MSL) [11], Phoenix Lander [12], and Insight Lander [13] all used relay spacecraft for high bandwidth (2-256 kbps) communication. Although DTE communications options also existed for these missions, the increased data-rate offered by relay spacecraft increased returned science data volume in all cases, as shown in Table 1. The Mars Reconnaissance Orbiter (MRO) [7], Mars Odyssey [6], and Mars Atmosphere and Volatile Evolution (MAVEN) [8] Mars-orbiting spacecraft have all served as relays for Martian surface craft after the conclusion of their primary mission. Relay-based communications have also been used outside of the Martian system, namely between the Jupiter-exploring Galileo spacecraft [14] and its probe and between the Saturn-exploring Cassini spacecraft [15] and its Huygens probe. In both cases, use of a relay communications architecture enabled the probes to return science data using reduced power and mass compared to a DTE architecture [10], [11].

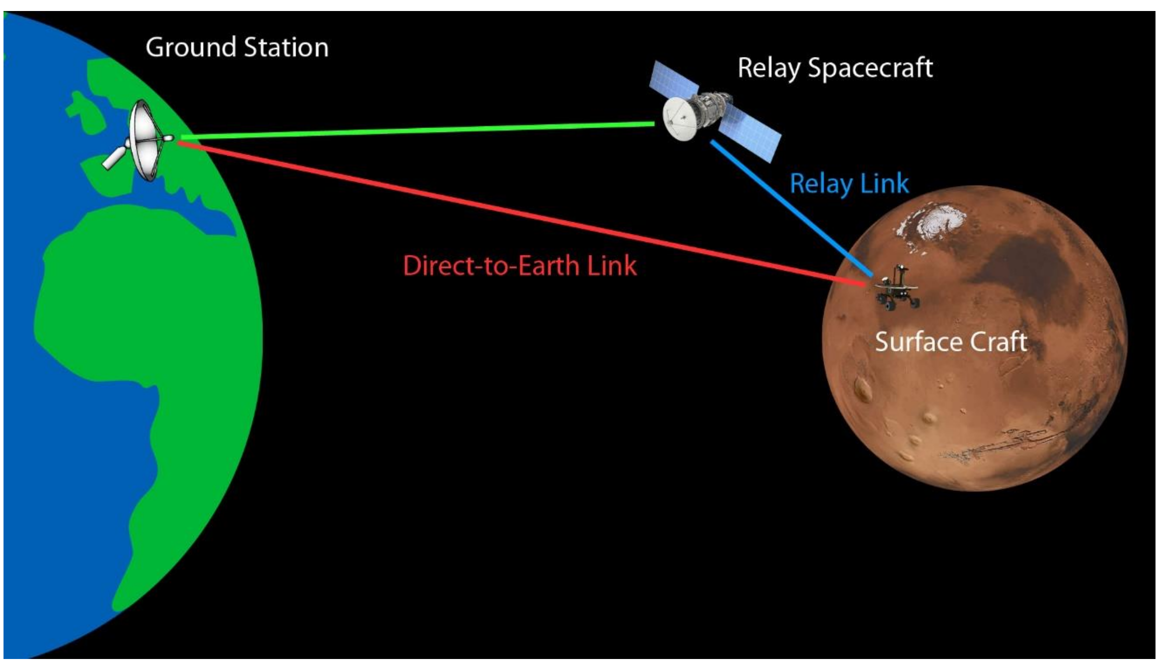

Figure 1: Direct-to-Earth and Relay Links for Earth-Mars Communication

Table 1: DTE vs Relay Communications for Selected Martian Surface Missions [10]–[12]

	DTE (X-band)					Relay (UHF)				
Craft	Downlink Data rate (kbps)	Power (W)	Mass (kg)	Ant-enna	Efficiency (kbps/W)	Downlink Data rate (kbps)	Power (W)	Mass (kg)	Antenna	Effic-iency (kbps/W)
Mars Science Lab	0.35 - 8.00	62.90	40.90	HGA	0.001-0.130	2.00 – 256.00	69.00	3.00	Quad-helix	0.029-3.700
Mars Explor-ation Rovers	3.50 – 12.00	71.80	6.80	HGA	0.056-0.190	128.00 – 256.00	43.00	1.90	Quarter-wavelength monopole	3.000-6.000
Phoenix Lander	N/A	N/A	N/A	N/A	N/A	8.00 – 128.00	52.20	6.50	Quad-helix, monopole backup	0.150-2.000

The increase in performance from using relay spacecraft is considerable; performance metrics for landers for which data is available is summarized in Table 1 above. MSL achieved a 21-36 fold increase in data-rate by using its relay system instead of its DTE system [12] and MER achieved a 5-32 fold increase [13]. Both rover designs were able to use lower mass systems, with the UHF systems weighing about 14 and 3.5 times less than their X-band counterparts, respectively [12], [13]. Assuming each rover was able to use the highest possible data rate for each communication mode, the communication efficiency increased by a factor of about 29 and 36, respectively, when using UHF instead of X-band communications [12], [13]. Based on the performance of the relay system on MER, the team designing the Phoenix lander chose to eliminate the DTE communication system from the design, saving an estimated 14.8 kg and more than $3 million [5]. Additionally, the relay systems were able to achieve their performance using statically mounted antennas, instead of the dynamic gimballing antennas used for the DTE systems [12]–[14]. Removing mechanical systems also removes failure modes of the communication subsystem due to breakdown of these mechanical elements, which could impair the antenna's ability to point accurately [5]. Damage of mechanical systems due to dust is a significant concern for Martian craft [15], therefore the ability to improve resilience to dust for a mission critical system like the communications system is crucial for the design of reliable surface missions.

While relays have benefitted previous Martian missions, future missions also stand to benefit from a relay communications architecture like MC3. The 2018 MEPAG report outlines NASA's goals, objectives, and priorities for Mars exploration, including a section on human exploration of the Martian system. From this document, Goal IV's Objective B is to *"obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with acceptable cost, risk, and performance,"* [4]. To better understand how MC3 can benefit the investigations necessary to achieve this objective, several investigations targeted at improving atmospheric models necessary for designing entry, descent, and landing stages for Mars, a sub-goal of Objective B, will be briefly considered.

Investigation B1.2 is to, *"monitor surface pressure and near surface meteorology over various temporal scales (diurnal, seasonal, annual), and if possible in more than one locale,"* [4]. To accomplish this, measurements of atmospheric parameters need to be taken simultaneously from a variety of locations on the surface and correlated with data collected from orbit [4]. One spacecraft concept designed for this investigation, among others, is the MARSDROP probe, a small (~3 kg) lander designed to fly as a secondary payload on future Mars missions. By using relay spacecraft to assist with communications, MARSDROP can use a two W, 55 g communications subsystem to meet its mission requirements [16]. The low power and mass of the subsystem is likely due to the 10-100 fold reduction in energy usage achieved by using a relay spacecraft instead of a DTE link [5]. Due to the low mass of the spacecraft, multiple MARSDROP landers can be added to future missions, allowing for data collection at a variety of surface locations [16]. Additionally, given the 99% daily coverage requirement of MC3, relay availability would be minimized as a design constraint when planning upcoming missions like MARSDROP.

Investigations B1.3, to *"make temperature and aerosol profile observations under dusty conditions (including within the core of a global dust storm) from the surface to 20 km (40 km in a great dust storm) with a vertical resolution of less than 5 km,"* and B1.4, to *"profile the near-surface winds (less than 15 km) with a precision below or equal to 2 m/s in representative regions[…] simultaneous with the global wind observations,"* both require in-situ atmospheric measurements to be taken above the Martian surface [4]. Proposed missions for addressing these investigations involve using rotorcraft [17], airplanes [18], or balloons [19] to take measurements over a long duration (hours to years), improving over short-duration measurements taken during the entry operation of previous surface missions. Similarly to surface missions, these craft benefit from relay availability in terms of increased data return, reduced energy and mass requirements, robust critical event communications, and increased communication opportunities [5]. The availability of relay spacecraft is considered an enabling capability for missions involving small craft like MARSDROP or the aircraft used to address investigations B1.3

and B1.4, due to the reduction in minimum weight and power for the communications system [5].

In addition to the goals directly relating to human expansion, multiple scientific goals would benefit from the availability of a communications constellation. Goal III Objective B's Investigation B1.2 suggests taking seismic readings from a variety of locations across Mars with a high degree of temporal accuracy [4]. Similarly to the atmospheric measurements discussed previously, these observations will also require contemporary measurements across multiple surface nodes; time-synchronization and return of this data could be accomplished by MC3. Additionally, some of the goals for investigating Mars' climate involve surface missions to the Martian poles [4]. These missions also benefit from the increased uptime a constellation would provide, and could be pursued at lower cost by using existing assets like MC3 instead of requiring a new relay orbiter or a higher-cost DTE communications system [5]. In addition, SKGs exist for both Martian moons [4], missions to which would also benefit from a nearby communications constellation for the same reasons missions to Mars itself would, although analysis of missions to these moons is beyond the scope of this review. The benefit of a communications constellation capable of providing high-bandwidth, low-power, and high-availability communication for craft operating in the Martian sphere of influence is well established; MC3 will be designed to provide these capabilities.

1.3 Scope

Due to the open-ended nature of both constellation and spacecraft design, proper constraints and assumptions are necessary to allow for completion of this thesis. First, optimization of the constellation configuration will not be attempted, as closed-form solutions for this problem type do not exist. There are a wide variety of interacting parameters yielding an infinite set of potential configurations. Only Walker Delta Pattern (WDP) constellations consisting of spacecraft in circular, polar orbits are investigated, as they are well suited to the complete coverage problem. Second, optimization of the communications system onboard the spacecraft will not be attempted, for the same reasons as the constellation configuration. The communications system is designed via link budget analysis. For both the communication and coverage problems, brute force techniques are used to find sufficiently optimal designs. A further discussion of WDP constellations and brute force techniques is presented in Chapter 3 of this thesis. Finally, the capabilities of the other subsystems onboard the spacecraft are compared to existing spacecraft that have successfully flight-proven these subsystems. The primary goal of this thesis is to demonstrate that a constellation can be designed that meets the requirements outlined in Section 1.1 using currently available technology. Possible routes to improving this design, both in terms of the cost of the system and its capabilities, will be discussed in Section 5.2 of this thesis.

Chapter 2

BACKGROUND

2.1 Orbital Mechanics

The field of orbital mechanics applies celestial mechanics to study the movement of objects accelerated primarily by gravity. A spacecraft's orbit can be described classically by a set of 6 elements: semi-major axis (a), eccentricity (e), inclination (i), argument of perigee (ω), right ascension of the ascending node (RAAN), and true anomaly (ν), illustrated in Figure 2 for the Mars centered inertial reference frame. Note that eccentricity is not shown. As this thesis will only consider circular orbits, eccentricity will always be set to zero and cannot be shown on a diagram of a circular orbit.

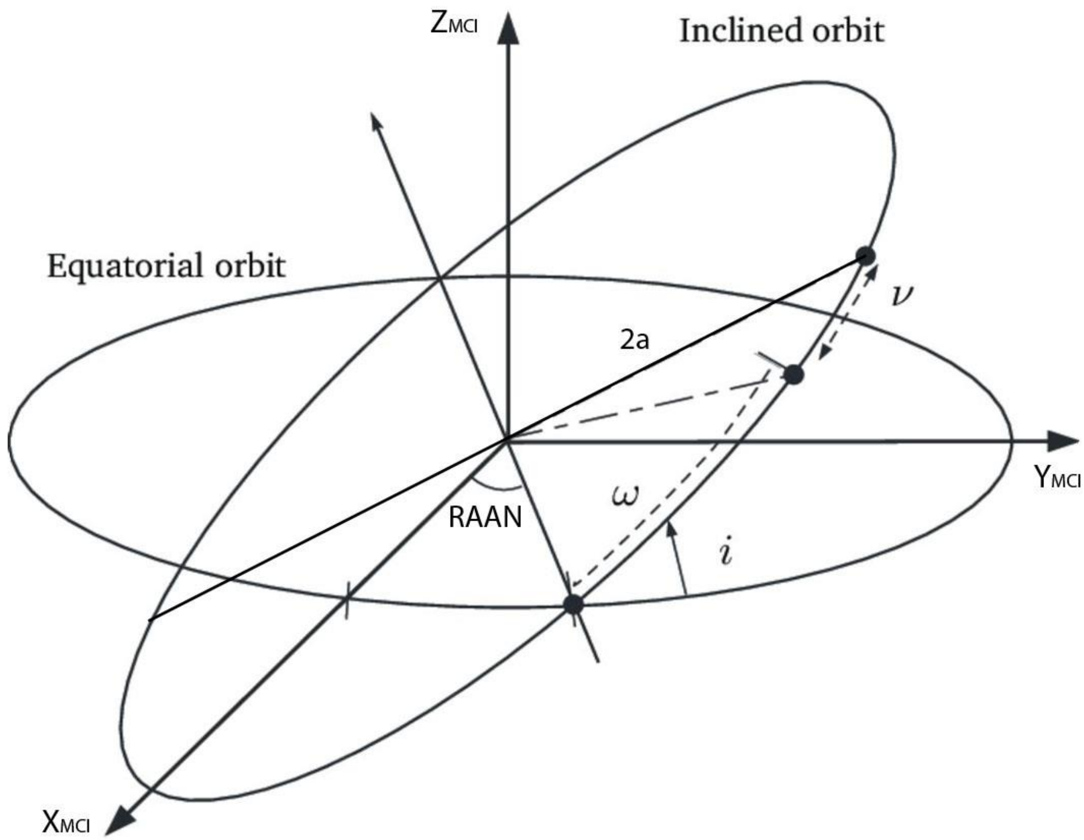

Figure 2: The Classical Orbital Elements (adapted from [21])

The size of the orbit is described by the semi-major axis, a, defined as half the distance between the points nearest and farthest from the center of the body. The shape of the orbit is given by the eccentricity e, which describes how elliptical the orbit is. The orientation of the orbit in three-dimensional space is given by the inclination, i, and the RAAN. The mean anomaly, ν, determines the spacecraft's position along the orbit. For the purpose of constellation definition, the inclination is the most important parameter, as it describes the tilt of the orbit relative to the equatorial plane. For an unperturbed orbit, where the spacecraft is only affected by the gravitational pull of a central body, the semi-major axis, eccentricity, RAAN, argument of periapsis, and inclination are constant. Orbital perturbations cause these elements to vary over time, and originate from a variety of causes, including the oblateness of the central body, solar radiation pressure, atmospheric drag, and the effects of other bodies, such as the Sun and moons of the central body [22]. For relatively high-altitude Martian orbits, these effects are mostly periodic and small in scale, and orbits in this thesis will be considered static except during discussion of long term stability.

2.2 Martian Relay Spacecraft

There are currently three spacecraft operating as relays in Martian orbit: Odyssey, MRO, and MAVEN. These spacecraft use UHF systems to communicate with Martian surface craft, and X-band systems to communicate with Earth [6]–[8]. The performance of Odyssey and MRO is given in Table 2, with MAVEN omitted due to a lack of published performance data. The downlink data rate in Gbits/sol is estimated as two 7-hour communication sessions with a 34 meter NASA Deep Space Network (DSN) dish per Martian day (sol) at the published minimum and maximum data rates for such a connection type. Based on the maximum return data rate of these relays, the total return data rate capacity of the current Mars relay system is between 151 and 775 Gbits/sol. Including a rough estimate of the capabilities of MAVEN, this would put the maximum total return data rate of the three relays around 1 Tbit/sol [8]. Given that Odyssey, MRO, and MAVEN started their extended missions in August 2004, November 2008, and November 2015, respectively, reliance on the continued operation of these spacecraft introduces additional risk to a mission plan [20]–[22]. However, the high power (Odyssey: 73.9 W and MRO: 165 W) and high mass (Odyssey: 17.3 kg and MRO: 94.4 kg) of the communications systems used in the relays preclude the use of this communication hardware on CubeSats given the lower power and mass available on the smaller platform [23]. This suggests that further investigation into the deep space communications hardware available to CubeSat-scale spacecraft is necessary.

Table 2: Performance Metrics for Selected Martian Relay Spacecraft [6], [7]

Craft	Relay to Earth Data Rate (Gbits/sol)	Earth to Relay Data Rate (bps)	Power (W)	Mass (kg)	Antenna
Odyssey	1-25	125	73.9	17.3	1.3 m HGA
Mars Reconnaissance Orbiter	150-750	15-2000	165	94.4	3.0 m HGA

2.3 Spacecraft Constellations

A constellation is a group of spacecraft distributed around a central body that work together to accomplish a common goal. There are an infinite number of possible constellation configurations that can meet the specific requirements of a given mission and a careful study of the performances of a given configuration is necessary. For a Martian communications network, the key requirement the constellation shall satisfy is complete continuous coverage of the entire Martian surface (Requirement 3).

In order to support expanded exploration of Mars, communications constellations in its orbit have been previously proposed. In 2000, NASA introduced a dual-purpose navigation and communications network concept dubbed MarsNet [24].

MarsNet would have used a low-orbiting constellation of 6 micro-spacecraft weighing about 220 kg each [24]. The first two spacecraft were to be placed in 172 degree Mars polar orbits at 800 km altitude, followed by four more at the same altitude, 111 degrees inclination, and equally spaced right ascensions [25]. Depending on the latitude of the surface asset, the system would have been capable of data rates around 200-400 Mbits/sol/W [24]. The target data return rate for the constellation was 100 Gbits/sol [24]. The goals of this constellation and the CubeSat constellation now proposed are quite similar. MarsNet intended to provide global coverage, redundancy against the loss of any single spacecraft, and increased data return from surface assets [25]. However, it intended to do this with a small quantity of relatively large spacecraft. For MC3, given the CubeSats used will be about two orders of magnitude lighter, a larger number of spacecraft will be necessary to meet the performance objectives. Additionally, constellation performance in terms of navigation capability was partially used to value configurations for MarsNet [25]. Since MC3 is not designed to provide navigation capabilities, the constellation analysis will result in a different recommended configuration.

In 2012, a study conducted by researchers at NASA's Jet Propulsion Laboratory (JPL) investigated the possibility of using a constellation of CubeSats as a communications network at Mars [26]. According to the researchers, an estimated 60 CubeSats would be needed for full coverage of the Martian surface, assuming an altitude similar to the roughly 280 km circular orbit of MRO [26]. Assuming patch antennas, 1 W transmitters, and 1000 km separation between CubeSats, the constellation would be capable of 600 bps crosslink [26]. However, neither analysis of the data return capability of the system as a whole nor analysis on optimizing the constellation parameters were part of the published data. CubeSat technology has progressed significantly since this study was conducted, and new analysis will be needed to determine how to best meet the 99% coverage and 1 Tbit/sol data volume requirements with a CubeSat-based network.

2.4 CubeSats

CubeSats are a subcategory of small spacecraft with a defined form factor and are designed to enable access to space for a larger community. After their co-joint invention in 1999 by Stanford and Cal Poly, CubeSats have become an increasingly popular spacecraft due to their lower cost and development time compared to traditional spacecraft [27]. CubeSats benefit from a strict design standard [27], allowing for commercial parts to be developed around a standardized form factor. The metric for describing a CubeSat's size is the U, a 10x10x10 cm cube. By this description, a 1U CubeSat is a 10 cm x10 cm x10 cm cube, while a 3U CubeSat is 30 cm x10 cm x10 cm. Although CubeSats are most popular for low-cost low Earth orbit (LEO) missions, recent missions have demonstrated the potential viability of using CubeSats in a Martian communication constellation [28].

The famous demonstrators of deep-space CubeSat relay technologies are the two MarCO spacecraft, 6U CubeSats flown as part of the InSight mission by JPL in 2018 [29]. The spacecraft were used to relay information from the InSight lander during its landing phase of operations, when the lander would have been incapable of DTE communication [29]. This capability was achieved by using a combination of two antennas: an X-band high gain reflectarray antenna for DTE communication, and a UHF loop antenna to receive data from the InSight lander [9]. This setup allowed for 8 kbps data downlink to Earth [29] on a system whose solar panels generated only an estimated

17 W while near Mars [9]. While the 8 kbps data rate was calculated based on the distance to Mars during InSight's landing operation (1.05 AU) [30], a data rate of 1.0 kbps was reported for the average Earth-Mars distance of 1.7 AU [31]. Since MarCO's primary mission was about 10 months, the lack of radiation-hardened electronics was handled by using software redundancy to back up key data and self-restore said data when faults were detected [30]. Although the spacecraft did not conduct orbital crosslink operations, the demonstrated capability of relaying science data from the surface of Mars to Earth via a CubeSat illustrates the feasibility of using CubeSats as interplanetary relays. Additionally, MarCO demonstrated the viability of CubeSats in deep space over short periods of time, verifying the feasibility of interplanetary flight and navigation, integration of CubeSats with a larger mission, and long-distance and long-delay communications using CubeSats [30]. Further analysis is needed to determine how CubeSats can perform these functions over a sufficiently long period to satisfy the 10 year objective.

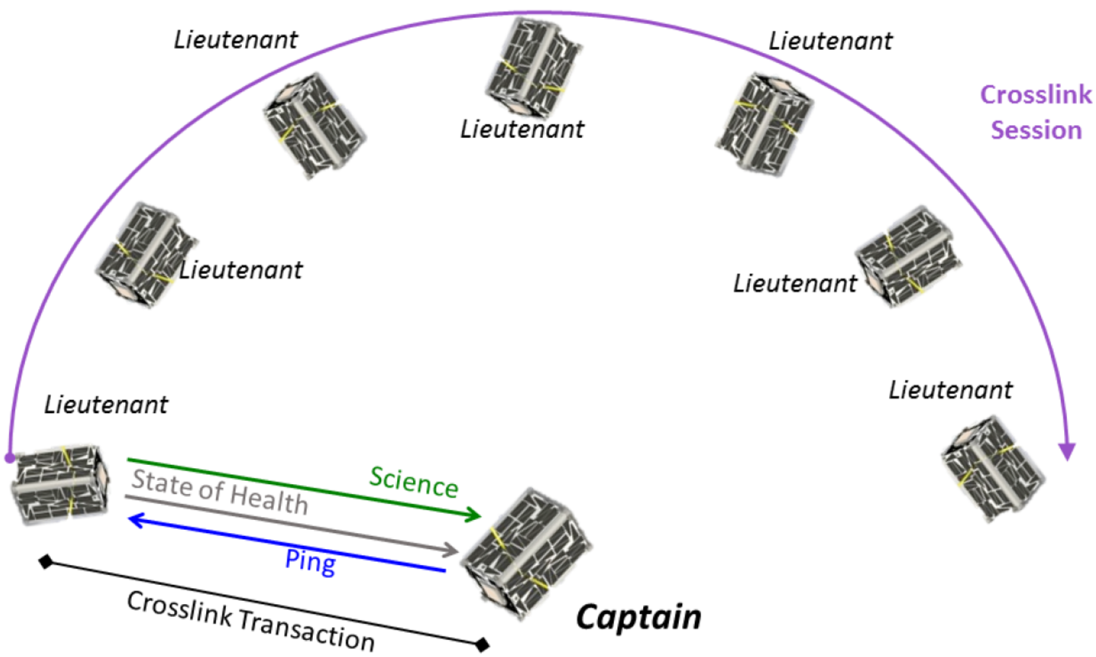

Figure 3: EDSN Communications Architecture [35]

In addition to relay capabilities, crosslink networking between CubeSats will be crucial for a constellation like MC3. The Edison Demonstration of Smallsat Networks (EDSN) was a swarm of eight 1.5U CubeSats developed by NASA Ames and launched in 2014 with the goal of demonstrating the capability of networked swarms of CubeSats in LEO. The mission collected multipoint ionospheric measurements from all spacecraft, transferred the measurements to a single spacecraft, and then transmitted the data to a ground station from this single spacecraft. To achieve this, the identical spacecraft took turns assuming the role of captain, the central node, while the remainder of the swarm were classified as lieutenants, as shown in Figure 5. Data packets contain a spacecraft-unique identifier so that only the intended unit will respond to the captain's requests for communication. When crosslink communications are not occurring for a given lieutenant, collected data is stored in a first-in-first-out queue for transmission to the captain during the next scheduled window. This system ensures that the most recent data is downlinked first, while ensuring data from one spacecraft does not push data from other spacecraft out of the captain's memory. The spacecraft used for this mission were relatively low power (1 W orbit average) and used exclusively commercial-off-the-shelf (COTS) components, including a UHF transceiver for crosslink capability and S-band transceiver for downlink capability. The mission demonstrated a networking concept, shown in Figure 3, enabling CubeSats to collect data from eight nodes, operate autonomously in LEO, downlink to ground stations via a central node, and maintain system operations in the case of failure of one or more spacecraft. While these capabilities do not precisely match the needs of a Martian constellation, they do provide flight proof of many of the required sub-operations of such a system, such as multipoint data collection, autonomous operation, data routing, and redundant operation. [32]

The combination of the MarCO and EDSN missions validates the capability of CubeSats to serve as autonomous deep-space relays, dynamically transfer data between nodes, and create self-configuring redundant architectures for network operations. However, multiple operational gaps still need to be filled before CubeSats can operate in a Martian constellation. For one, the ten year required lifespan of the MC3 program (Requirement 4) must be considered. Assuming Hohmann transfers, Earth-to-Mars transfer windows occur roughly every 26 months. The transfer itself takes roughly nine months, meaning that MC3 CubeSats will need to operate for 35 months at a minimum before replacement is possible. The MarCO spacecraft had a straightforward primary mission, only needing to relay data for the entry, descent, and landing phase of a single spacecraft (InSight) back to the Earth over a roughly half-hour period near the conclusion of its 10-month primary mission [30]. Both the EDSN and NODeS missions operated with their CubeSats in a swarm, with each spacecraft continually in communication range of the others [32], [33]. Extending these capabilities to match the needs of the MC3 program requires the implementation of delay/disruption tolerant networking and hardware that can maintain operations in Martian orbit over at least a 35 month duration.

2.5 Program Architectures

Two types of architectures were identified early in the research process that had the potential to meet the stakeholder requirements outlined in Section 1.1 and justified through Chapter 2. Both architectures use a constellation of CubeSats to shorten the communication distance for the spacecraft operating on the Martian surface. The first architecture, illustrated in Figure 4, is a CubeSat-only architecture, with the CubeSats handling both the communication link with the surface spacecraft (Link 1) and the communication link with the ground station on Earth (Link 2).

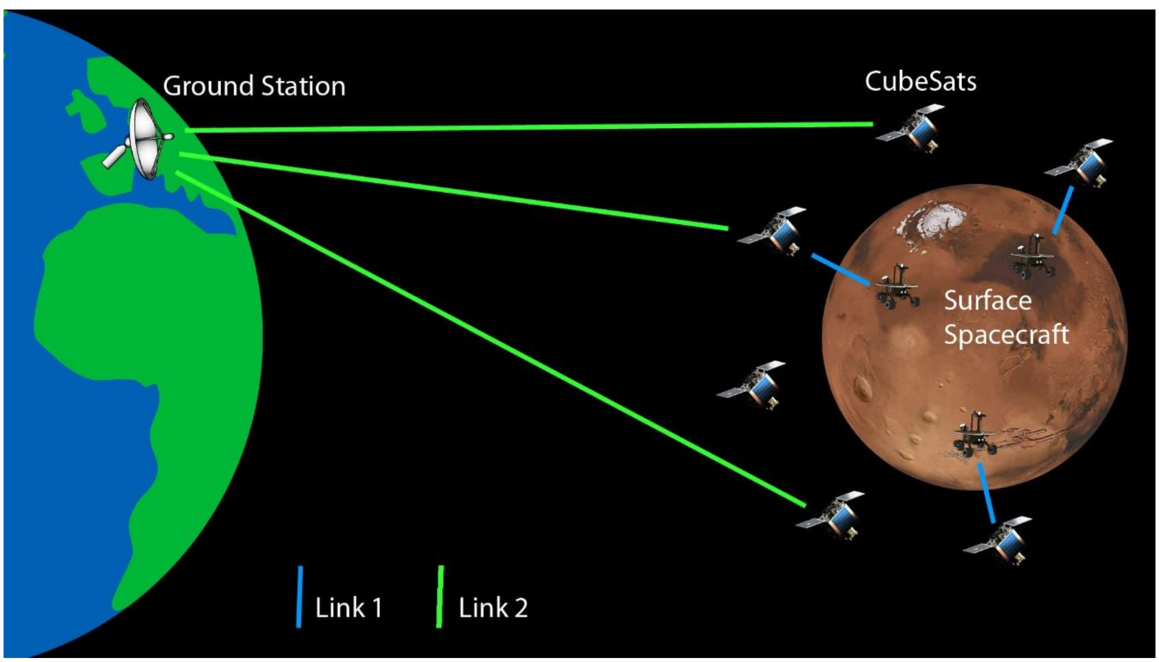

Figure 4: CubeSat-Only Architecture

While CubeSats are readily capable of closing Link 1 at data rates sufficient to meet Requirements 1 and 2, as will be presented in Section 4.3, the long communication distance associated with Link 2 (about 270 million km on average [34]) presents a significant challenge. Due to the form factor restrictions imposed by the CubeSat design specification [27], Size, Weight, and Power (SWaP) budgets are tightly constrained. The PolySat organization gives bus capabilities for the one, two, and three-U form factors for Earth-orbiting CubeSats, which are given in Table 3 along with conservative approximations for six and twelve-U form factors. Relocating the CubeSats to Mars further decreases these budgets, specifically cutting power generation by about 60%, assuming solar panels are the power generation method. Radio systems typically have efficiencies of about 50%, resulting in a final radio frequency (RF) power delivery of about 10 W maximum, even for a 12 U CubeSat. As will be demonstrated in Section 4.3, the Size Weight and Power (SWaP) constraints, specifically this power constraint, combined with the antenna size restrictions imposed by the size and weight budgets, results in Link 2 failing to close at a sufficient data rate to satisfy Requirement 1.

Table 3: CubeSat SWaP Margins for LEO

CubeSat Nominal Size	1 U	2 U	3 U	6 U	12 U
Available Volume	2/3 U	1 2/3 U	2 2/3 U	5 1/3 U	11 U
Available Mass	.5 kg	1.2 kg	2.5 kg	4.5 kg	8 kg
Available Power in full Earth sunlight (Static / Deployable)	2 W	5 W	8 W / 18 W	17 W / 30 W	30 W / 50 W

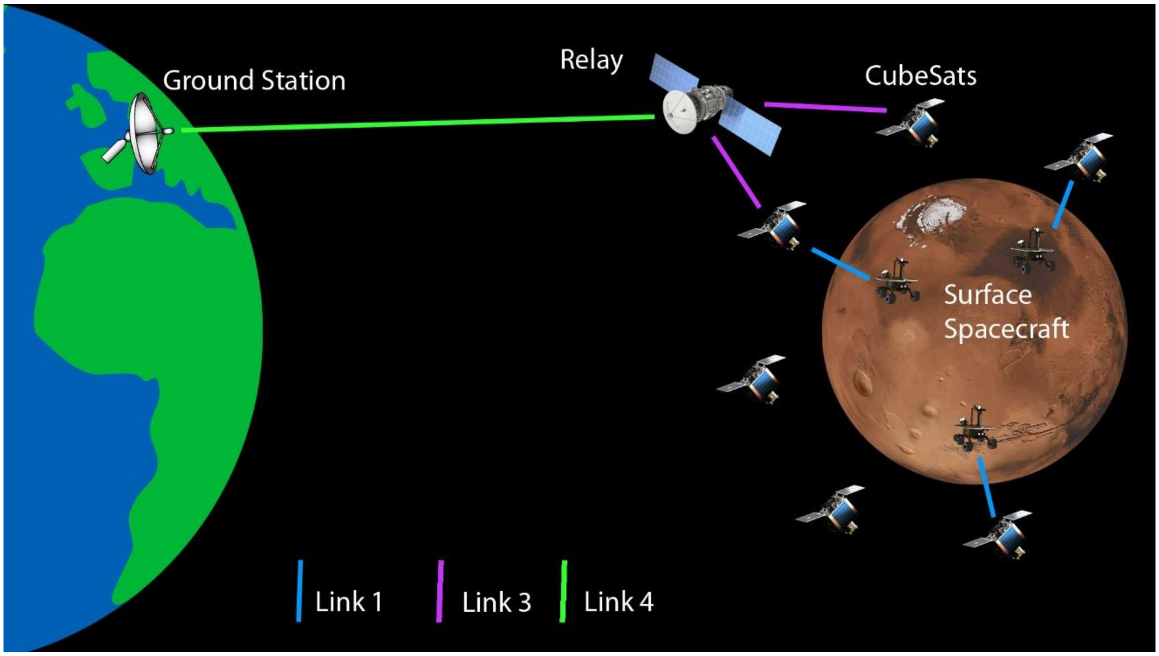

Figure 5: CubeSat and Relay Architecture

The solution to this problem is the addition of a larger relay satellite in Martian orbit, hereafter referred to as the Relay, resulting in the architecture presented in Figure 5. The communication link to Earth (Link 4) can now be handled by a spacecraft free of the SWaP constraints imposed on CubeSats, therefore capable of providing the data rates to satisfy Requirement 1. The constellation of CubeSats continues to satisfy the coverage requirement (Requirement 3) and is more than capable of closing the remaining link, Link 3, with a sufficient data rate to satisfy Requirement 1. A specific configuration of this architecture type results in the recommended architecture for precisely meeting the stakeholder requirements, justified in Section 4.4, is presented graphically in Figure 6, and summarized in Table 4.

Table 4: Recommended Architecture Parameters

CubeSats:	Orbital Radius	# of Planes	# of Satellites Per Plane
	4700 km	2	9
	Antennas	Transmitters	
	2 x UHF 1/4-length monopole antenna	4 W RF UHF Transmitter (downlink) 1 W RF UHF Transmitter (uplink)	
Relays:	Orbital Radius	# of Planes	# of Relays Per Plane
	5996 km	2	2
	Antennas	Transmitters	
	6-m Earth-facing dish 0.34 x 5-m Mars-facing antenna	50 W RF Ka-band Transmitter (downlink) 1 W RF UHF Transmitter (uplink)	
Downlink Data Rate (Constellation)		Uplink Data Rate (per Surface Craft)	
11.7 Mbps		110 kbps	

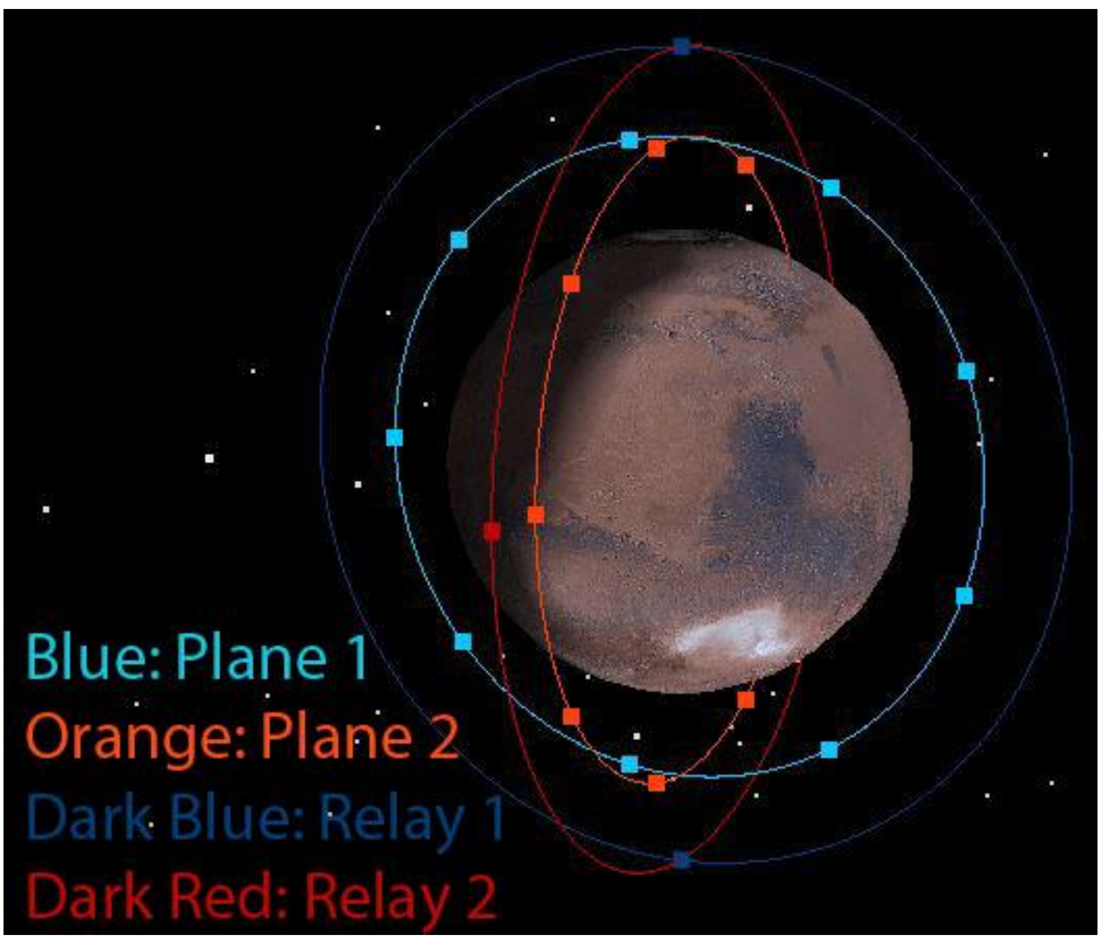

Figure 6: Recommended Architecture

CHAPTER 3

METHODOLOGY

3.1 Coverage Analysis

The goal of the coverage analysis is to identify WDP constellation configurations that meet the 99% coverage requirement (Requirement 3). Coverage is defined here as the percentage of Mars' surface that has line-of-sight (LOS) access to any CubeSat in the communication constellation. To compute this percentage, the Systems Tool Kit (STK) version 11.6.0 software package from Analytical Graphics Inc. was used in conjunction with its Analyzer add-on module.

Table 5: Input Parameters for Coarse Study

Parameter	Lower Bound	Upper Bound	Step Size
Orbital Radius	3700 km	7700 km	500 km
# of Planes	2	4	1
# of Spacecraft per Plane	3	9	1

Table 6: Input Parameters for Fine Study

Parameter	Lower Bound	Upper Bound	Step Size
Orbital Radius	3700 km	4700 km	100 km
# of Planes	3	5	1
# of Spacecraft per Plane	3	15	1

The coverage analysis utilized a brute force approach consisting of two phases: a coarse study and a fine study. The goals of the coarse study are to determine valid high-altitude constellation configurations as well as the region(s) of the design space that require fine study. The goal of the fine study is to determine valid low-altitude constellation configurations in the region(s) identified by the coarse study. Each study considered only WDP constellations consisting of spacecraft in circular, polar orbits (eccentricity = 0 and inclination = 0 degrees). As such, each possible constellation could be defined by three input parameters: Orbital Radius, Number of Planes, and Number of Spacecraft per Plane. The input parameters for the coarse study are given in Table 5. The input parameters for the fine study, derived from the coarse study results (which are discussed in detail in Section 4.1), are given in Table 6.

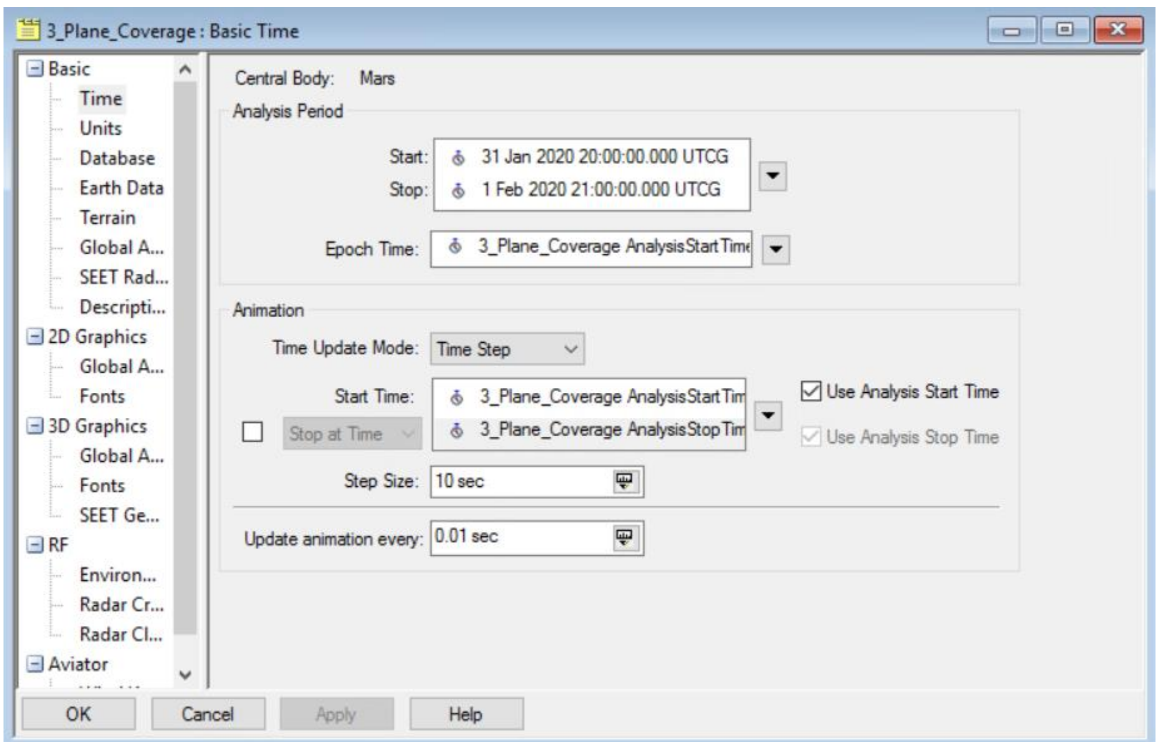

Figure 7: STK Scenario Configuration

Each study was investigated using separate STK Scenarios. To set up each Scenario, several parameters were changed from their default values, as shown in Figure 7. The Basic parameter Central Body was changed from “Earth” to “Mars”. The time parameter Analysis Period was changed to start at 31 January 2020 20:00:00 Gregorian

Universal Time (UTCG) and end at 1 February 2020 21:00:00 UTCG. The analysis duration was selected to be 25 hours to allow for a full Martian day to be analyzed, while the start date and time were arbitrarily chosen. All other Scenario parameters were left at their default values. Thus configured, each scenario was populated with three types of objects: Coverage Definitions, Satellites, and Constellations.

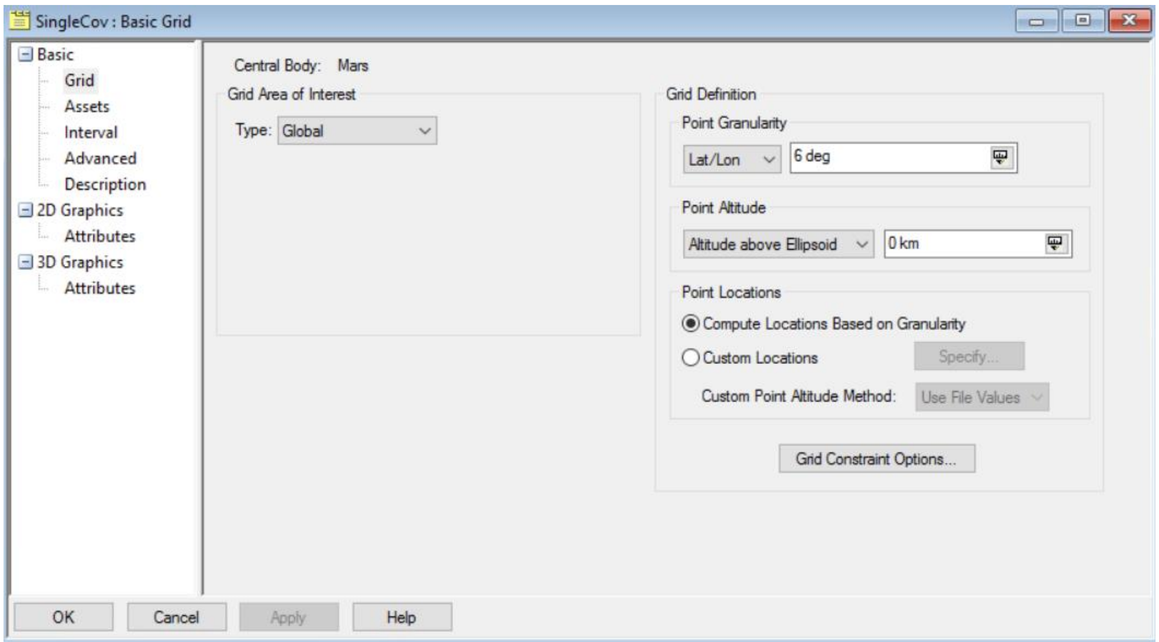

Figure 8: STK Coverage Definition Configuration

A Coverage Definition object is used to define the area of interest for the coverage calculation and to approximate it via coverage points. First, the grid parameters are specified, as shown in Figure 8. Grid Area of Interest is set to the "*Global*" type, as this thesis is interested in coverage of the entire Martian surface. Under Grid Definition, Point Granularity was set to "*Lat/Lon*" at six degrees and Point Altitude is set to "*Altitude above Ellipsoid*" at zero km. This combination of parameters results in a grid consisting of coverage points defined by the centers of six by six degree squares that span the entire Martian surface, as shown in Figure 9. A grid resolution of six by six degrees was selected as it is the recommended default configuration for coarse studies [35] and because the roughly 2000 coverage points it creates is well in excess of the 100 that would be needed to evaluate the 99% requirement. Based on the coarse study results, the amount of spacecraft being analyzed was expected to increase by a factor of around three for the fine study. The Point Granularity was therefore reduced for the fine study by a factor of three to two degrees to compensate for the additional spacecraft being analyzed.

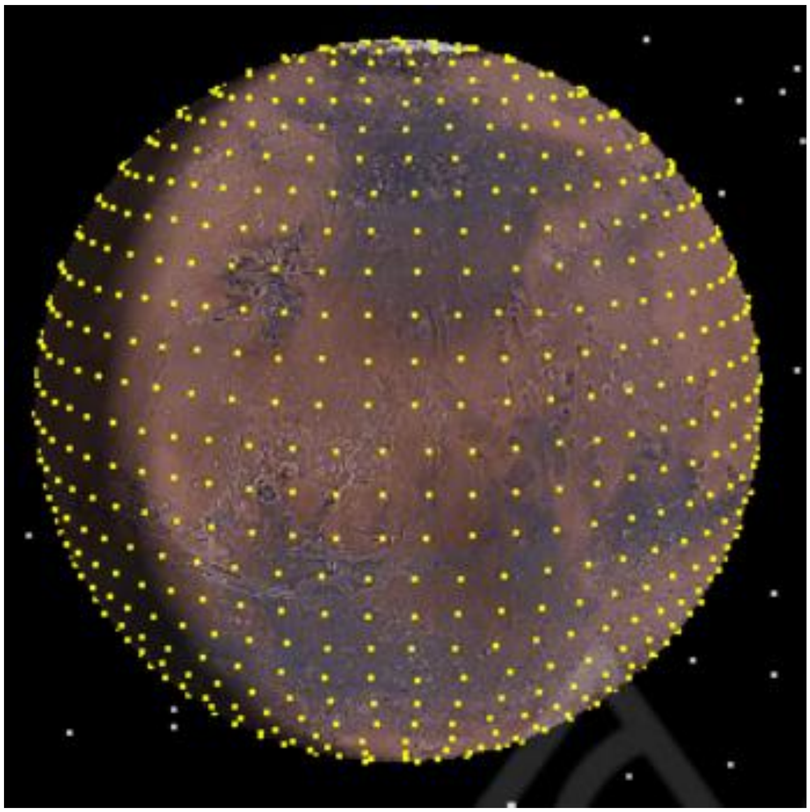

Figure 9: Coarse Coverage Grid

With the coverage grid defined, the spacecraft each coverage point needs to check LOS access for must now be defined. Under Assets, the “CubeSats” Constellation is assigned with Grouping set to “Separate.” When the simulation is run, each spacecraft in the “CubeSats” Constellation is separately analyzed to determine when it has LOS access to each coverage point. All other parameters for the Coverage Definition are left at their default values.

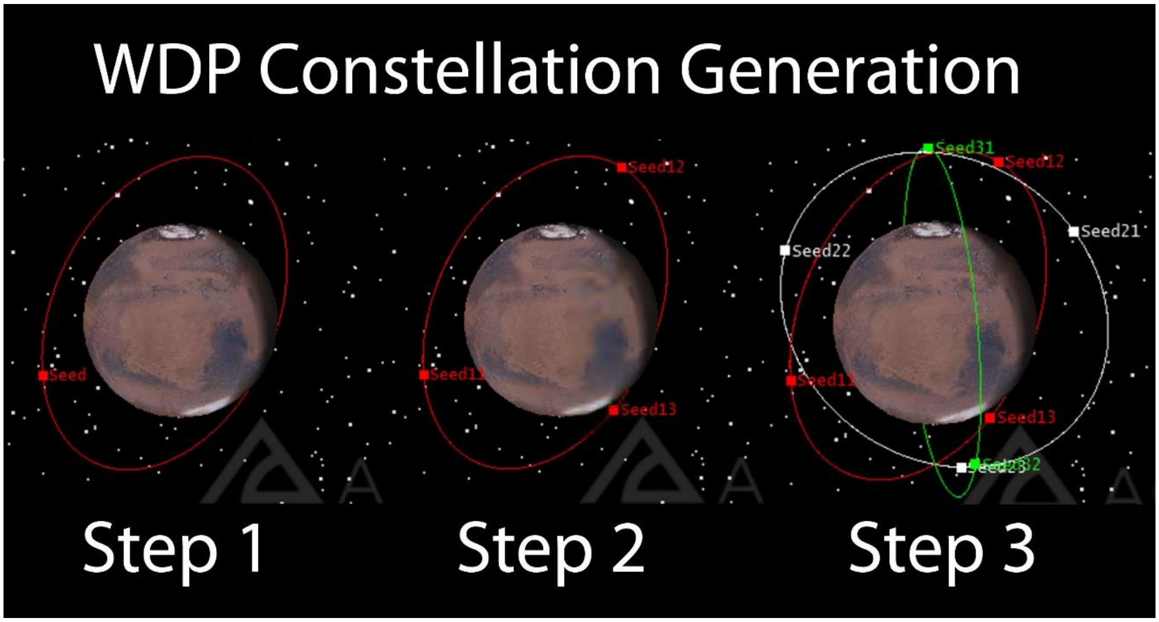

Figure 10: WDP Constellation Configuration

With the Coverage Definition configured, the "CubeSats" Constellation must be constructed. The Constellation is constructed with the Walker tool, which creates WDP constellations from a seed Satellite and three additional parameters, Type, Number of Planes, and Number of Satellites per Plane. In step 1, the seed Satellite defines the orbital radius, inclination, eccentricity, and RAAN of the first orbital plane, as well as defining the true anomaly of the first Satellite within this plane. In step 2, the Walker tool then populates the first plane with additional copies of the seed Satellite, evenly spaced in terms of true anomaly, until the target Number of Satellites per Plane is met. In step three, the Walker tool generates copies of this fully-populated plane, evenly spaced in terms of RAAN, until the target Number of Planes is reached. The Type parameter has two possible arguments, "Delta" and "Star", which determine whether the RAAN values for each plane will be spread from zero to 180 or from zero to 360 degrees, respectively. This three-step process is illustrated in Figure 10 for a Seed Satellite in a 5700 km radius, zero inclination, zero eccentricity (polar and circular) orbit, Type set to "Delta", and with the Number of Satellites per Plane and Number of Planes set to three. Once these Satellites have been generated, they must added to the “CubeSats” constellation (via the Assets tab) before the coverage results can be calculated.

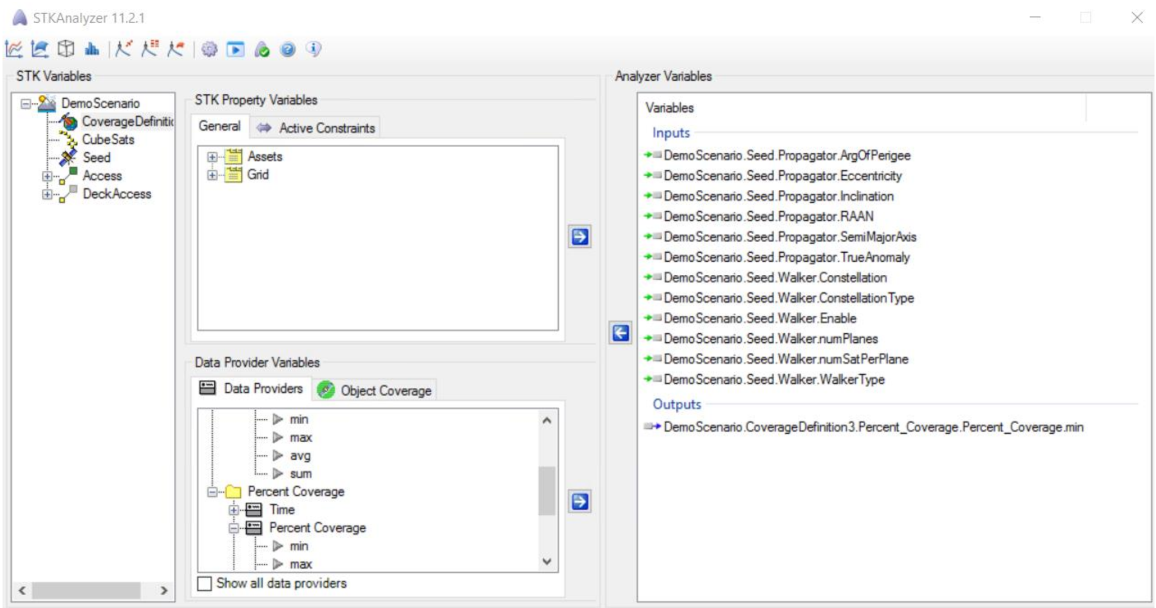

Figure 11: Configuration of Analyzer Parameters

Given the large number of configurations to be analyzed (189 for the coarse study), automation of the coverage analysis is highly desirable and is achieved by using STK’s Analyzer module. This technique was used to generate all of the coverage analysis results, which are presented in Section 4.1. First, the Scenario and Coverage Definition are created and configured as described above. Next, the seed Satellite is created, leaving all parameters to their default except Propagator, which is set to *“J4Perturbation.”* The J4 propagator is used since it accounts for the roughly 99% of the perturbation effects experienced by Mars-orbiting spacecraft, a conclusion justified in detail in Section 4.2. All Satellites generated by the Walker tool carry the properties of the seed Satellite with them (with the exception of RAAN and true anomaly as these must be changed to place each Satellite in its proper orbit), so this propagator is used by all Satellites in the generated constellations. The *"CubeSats"* Constellation is then created and the seed Satellite is assigned to it via the Assets tab.

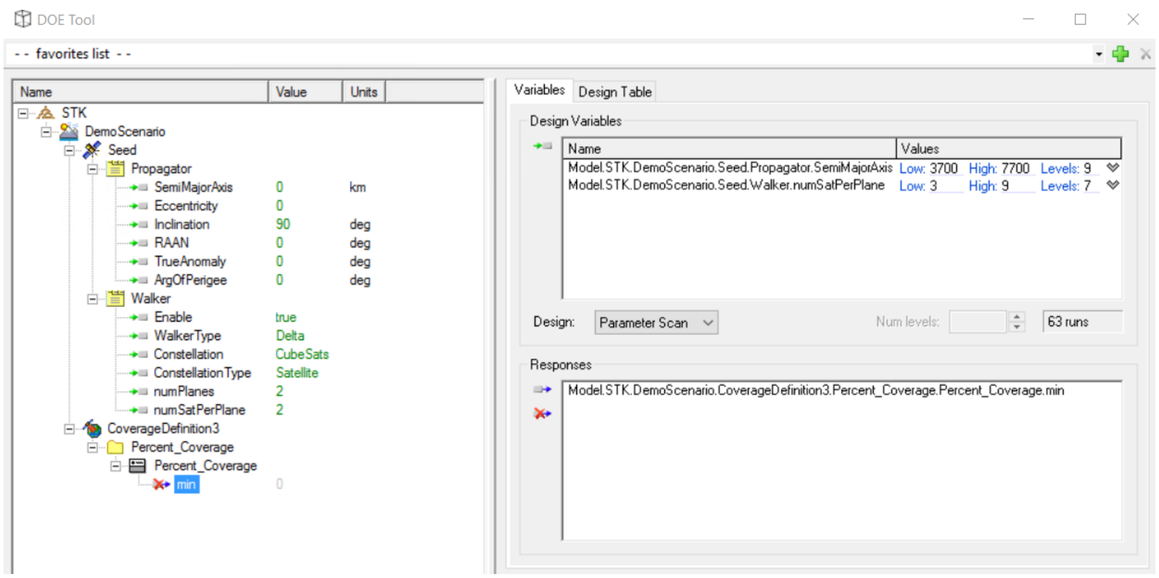

Figure 12: Configuration of the Design of Experiments Tool

With the Scenario created and populated with the Coverage Definition, seed Satellite, and *"CubeSats"* constellation, Analyzer is launched and configured to automate the coverage analysis process. As shown in Figure 11, the appropriate input parameters from the seed Satellite (ArgOfPerigee, Eccentricity, Inclination, RAAN, SemiMajorAxis, and TrueAnomaly from the Propagator tab, as well as Constellation, ConstellationType, Enable, numPlanes, numSatPerPlane, and WalkerType from the Walker tab) and output parameter from the Coverage Definition (Percent_Coverage.Percent.min) are added to Analyzer. The minimum value for percent coverage is used since, as Requirement 3 specifies continuous coverage, any drop below 100% coverage means that the constellation configuration being tested is not a valid solution. With the parameters loaded, the Design of Experiments tool is launched and the input parameters are set, as shown in Figure 8 for the two plane case from the coarse study. The Design Variables tab on the right side of the Figure 12 shows the two parameters to be varied by Analyzer, semi-major axis (equivalent to orbital radius for circular orbits) and number of satellites per plane. Unfortunately, the number of planes cannot be varied here, as the WalkerType parameter must be set to *"Delta"* for constellations with an odd number of planes and to "Star" for constellations with an even number of planes for proper RAAN spacing of the planes to occur. The other input parameters, shown on the left side of Figure 12, hold the static value assigned unless the parameter is also assigned as a Design Variable. In this way, Analyzer was used to conduct the coverage analysis for all possible combinations of orbital radius, number of planes, and numbers of satellites per plane specified for the coarse and fine studies. The configurations that met Requirement 3 were identified, and the assembled results are presented in Section 4.1.

3.2 Stability Analysis

The goal of the stability analysis is to demonstrate the orbital stability of the constellation configurations identified in Section 4.1, as well as to identify any unstable configurations so that they can be removed from further consideration. Since all real orbits are unstable to some degree, the emphasis of this analysis will be on the stability of each constellation as a whole. The stability of a constellation is defined here as the degree to which a constellation maintains its initial geometry in terms of semi-major axis, inclination, and RAAN spacing over the 35-month lifetime of the CubeSats within the constellation. Stability analysis of the Relay satellite(s) will not be conducted, as the delta-V capability of the Relay(s), which determines their ability to correct for orbital perturbations, is not limited by SWaP restrictions, unlike the CubeSats, which are restricted by the CubeSat design specification [27]. STK is used to propagate the perturbed satellites, while MATLAB is used for analysis and graphing of the resulting data. During the RAAN spacing analysis, MATLAB was used in place of STK for propagation due to a technical issue that will be covered in greater detail in Section 4.2.

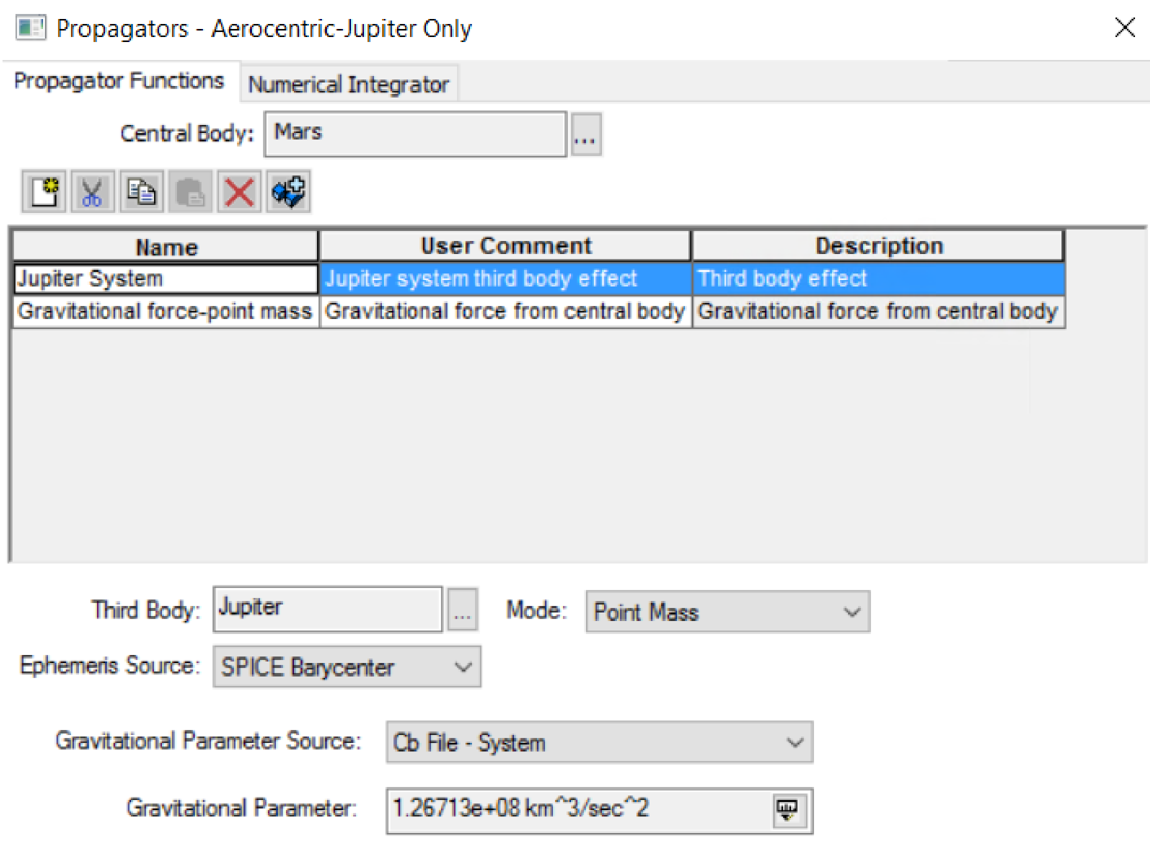

Figure 13: Propagator for the Third-Body Effects of the Jupiter System

To determine which perturbations should be included in the stability analysis and which should be neglected, six perturbing forces were considered in order to determine their relative magnitudes: solar radiation pressure (SRP), non-sphericity of Mars, atmospheric drag, and third-body effects from the sun, Martian moons, and the Jovian system. To determine the effect of each perturbation, each was isolated and modeled by a separate STK Propagator component, which could then be simulated using STK's Astrogator module. Each of these Propagators modeled the perturbing force as well as the gravity of Mars as approximated by a point mass. Each Propagator used the Runge-Kutta-Fehlberg 7th/8th order (RKF78) integrator, which was chosen because it is the integrator recommended by AGI for general use [36]. The Propagator isolating the third-body effect of the Jovian system is shown in Figure 13 as an example. For SRP and atmospheric drag, the CubeSat was approximated as having a cross-sectional area of 0.25 m^2 and a mass of 12.5 kg, roughly equal to the cross-sectional area and mass of the MarCO spacecraft [30], and SRP and drag coefficients of 1 and 2.2, respectively. Atmospheric drag was modeled using the STK's exponential model for the Martian atmosphere. Non-sphericity was modeled up to degree and order 20 using the MRO gravitational model.

Table 7: Perturbation Effects on a CubeSat in a 4200 km Reference Orbit

Perturbation	Non-Sphericity	Solar Radiation Pressure	Atmospheric Drag	Third-body – Martian Moons	Third-body – Jupiter	Third-body – Sun
Displacement (km)	4260	47.8	0	0	9.34e-5	1.30

Each perturbation's Propagator was used with the Astrogator module to model the trajectory of a CubeSat in a 4200 km circular polar initial orbit for its 35 month lifetime, after which the maximum deviation from a reference unperturbed orbit was calculated. It is worth noting that these displacements may be in any direction from the initial orbit, so they do not necessarily indicate a change in orbital size. These displacements are given in Table 7. Based on the displacements calculated for each perturbation, it was determined that the third body effects from the Martian moons, the Jovian system, and the Sun could be neglected in the rest of the stability analysis due to their negligible effect on the displacement of the CubeSat (less than 0.1% of total displacement in all cases). It was also determined that atmospheric drag could be neglected for orbits at a radius of 4200 km or higher, since no measureable effect was determined at this radius and the magnitude of atmospheric drag strictly decreases as orbital radius increases. For orbits below this radius, drag would be included, since its effect was expected to increase at lower altitudes. The non-sphericity and SRP perturbations would be included in all orbits analyzed as they both produced significant displacement.

With the relevant perturbations identified, each constellation configuration would be simulated in STK under the effect of those perturbations to determine its stability. First, an orbit with zero initial RAAN would be analyzed as a representative orbit for each orbital radius that supported a valid constellation configuration, as determined by Section 4.1. This orbit is used to determine inclination and semi-major axis stability for constellations at that orbital radius. Next, additional orbits would be modelled for each initial RAAN value possible (i.e. zero, 120, and 240 degrees for a 3 plane configuration) at each radius to determine the stability of the RAAN spread for each identified configuration. All orbits evaluated were given initial true anomalies and arguments of perigee of zero. All orbits were evaluated from 22 Apr 2023 20:00:00 UTCG until 22 Apr 2033 UTCG. The ten-year timespan was selected such that, in the event the CubeSats survived beyond the 35-month minimum, the stability of their constellation would be known. The 22 Apr 2023 start date was selected as it is the arrival date corresponding to the Hohmann transfer available during the next Earth-Mars transfer window. The results of these analyses are presented in Section 4.2.

3.3 Link Analysis

Link budget analysis was employed to find communication system configurations that could meet the 1 Tbit/sol downlink requirement (Requirement 1) and the 1 kbps uplink requirement (Requirement 2). This analysis was conducted for each possible link of the architectures identified in Section 2.5. The links are:

- Link 1: CubeSat and a spacecraft on the Martian surface
- Link 2: CubeSat and a ground station on Earth
- Link 3: Relay spacecraft in Martian orbit and a CubeSat in Martian orbit
- Link 4: Relay spacecraft in Martian orbit and a ground station on Earth

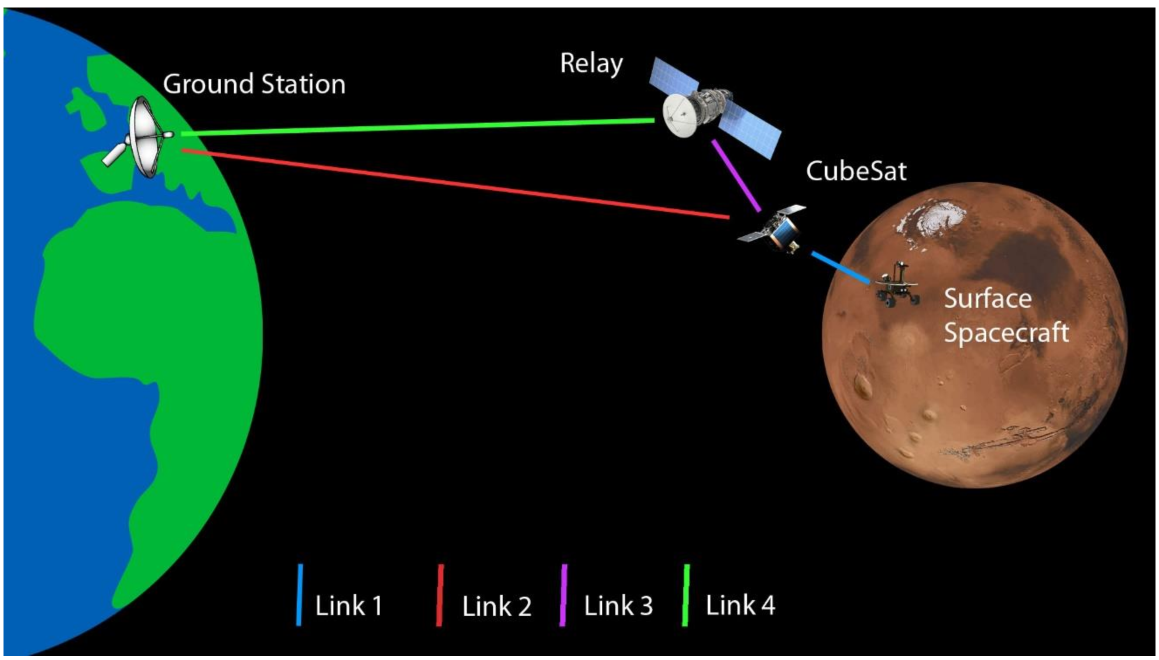

Figure 14: Possible Link Elements

An illustration of these links is presented in Figure 14. Downlink is defined as the Mars-to-Earth direction, and uplink is defined as the Earth-to-Mars direction.

To perform the analysis, a combination of methods were used from [37] and [38]. The data rate, R (dB-Hz), is calculated according to Equation 1. According to Equation 2, reception and transmission gains, G_{TX} and G_{RX} (dB), are calculated for parabolic antennas from the RF frequency, f (GHz), the dish diameter, D (m), and the dimensionless antenna efficiency, η. The constant 20.5 represents the conversion from Hz to GHz, as well as the π and light-speed terms that result from using frequency instead of wavelength. For Links 1 and 2, other antennas, such as patch and monopole antennas, are also used. Their gains are specified when used in Section 4.3. The transmission power, P_{TX} (dB-W), is converted to its logarithmic form using Equation 3. Equation 4 converts the Boltzmann constant, k (J/K), to its logarithmic form K (dB-J/K). The system noise temperature, T (K), is calculated from the antenna noise temperature, T_A (K), and the dimensionless noise figure, F, by Equation 5. The reference temperature T_0 is 290 K. Equation 6 converts the system noise temperature, T (K), to its logarithmic form T_S (dB-K). Equation 7 calculates the free-path loss, L_S (dB), from the communication frequency, f (GHz), and the distance between transmitter and receiver, r (km). The constant 92.45 represents the conversions from Hz to GHz, m to km, and the π and light-speed terms that result from using frequency instead of wavelength.

$$R = G_{TX} + G_{RX} + P_{TX} + K - T_S - L_S - L_O - Eb/No$$

Equation 1: The Link Budget Equation

$$G = 20.5 + 20\log(f) + 20\log(D) + 10\log(\eta)$$

Equation 2: Parabolic Antenna Gain

$$P_{TX} = 10\log(P(W))$$

Equation 3: Decibel Conversion of RF Power

$$K = 10\log(k)$$

Equation 4: Decibel Conversion of the Boltzmann Constant

$$T = T_A + (F - 1)T_0$$

Equation 5: Calculation of System Noise Temperature

$$T_S = 10\log(T)$$

Equation 6: Decibel Conversion of System Temperature

$$L_S = 92.45 + 20\log(r) + 20\log(f)$$

Equation 7: Calculation of Free Path Loss

Due to a lack of real hardware with published performance parameters, several conservative approximations had to be made to facilitate the link budget calculations. Four commonly used frequencies were analyzed, and the following representative frequency values were used: 0.44 GHz for UHF, 2.1 GHz for S-band, 8.43 GHz for X-band, and 32.2 GHz for Ka-band. Teledyne Defense Electronics manufactures low noise amplifiers with noise figures below 2 dB for all frequencies analyzed [37]. Since the noise figure for the radio system is generally dominated by the low noise amplifier, a noise figure of 2 dB was assumed for the calculation of system noise temperature. Antenna noise temperature values are taken from [38] for all downlinks and the Link 1 uplink and from [39] for the Link 2, 3, and 4 uplinks. These values, along with the system noise temperatures, are given in Table 8 for each link segment and frequency.

Table 8: Antenna and System Noise Temperature

	T_A (UHF) (K)	T_A (S-Band) (K)	T_A (X-Band) (K)	T_A (Ka-Band) (K)	T (UHF) (K)	T (S-Band) (K)	T (X-Band) (K)	T (Ka-Band) (K)
Link 1: Downlink	155	185	191	193	324.6	354.6	360.6	362.6
Link 2: Downlink	155	185	191	193	324.6	354.6	360.6	362.6
Link 3: Downlink	88	27	32	117	257.6	196.6	201.6	286.6
Link 4: Downlink	88	27	32	117	257.6	196.6	201.6	286.6
Link 1: Uplink	54	9	4	3	223.6	178.6	173.6	172.6
Link 2: Uplink	10	3	3	3	179.6	172.6	172.6	172.6
Link 3: Uplink	10	3	3	3	179.6	172.6	172.6	172.6
Link 4: Uplink	10	3	3	3	179.6	172.6	172.6	172.6

The margin for link budget closure was chosen to be 3 dB, equivalent to a factor of safety of two. Antenna efficiency was assumed to be 0.5 for all parabolic dish antennae [40]. Moreover, an additional 5 dB margin accounts for unconsidered losses, such as line and pointing losses. Turbo codes were used due to their high performance at low signal to noise ratios. 1/2 rate Turbo encoding was assumed, giving a target Eb/No of 1.2 dB for the assumed bit error rate of 1e-6 [41]. Due to the absence of Martian precipitation and the thin atmosphere of Mars in general, atmospheric attenuation was assumed to be 0 dB for the Martian atmosphere, while Earth atmospheric attenuations of 0.74 and 0.08 dB were used for Ka and X-band, respectively. The Earth attenuation values were estimated based on the average of the 99% monthly worst case attenuations at the DSN complexes located in Canberra, Australia, Madrid, Spain, and Goldstone, CA, USA [38], since DSN equivalent ground stations are assumed. An Earth-Mars representative distance of 227 million km was calculated by taking the logarithmic average of the Earth-Mars distance over the last 100 years, using JPL's Horizons database as the instantaneous distance source [34]. Microsoft Excel and MATLAB were used to calculate link budget results, which are presented in Section 4.3.

3.4 Architecture Analysis

Trade studies were employed to determine the best constellation configuration from those identified in Section 4.1 based on the following parameters: total number of spacecraft, number of planes, and data rate. The total number of spacecraft was included to account for the cost of manufacture for each individual CubeSat. The number of planes was included to account for the cost of delivering the CubeSats to each individual plane. The number of spacecraft to be delivered to each plane is assumed to have a negligible impact on this cost. The data rate was included to account for the benefit of additional data capacity beyond the necessary 1 Tbit/sol. The data rate was calculated as the total data throughput possible for a given configuration, assuming the maximum performance option identified in Section 4.3 for each link segment is used. An example is given in Table 9 for the 3 plane, 4700 km radius case.

Table 9: Data Rate for 3 Plane, 4700 km Case

Total Spacecraft	Surface Link	Cube Relay Link	Total Surface Link	Total Cube-Relay Link	Relay-Earth Link	Total Relay-Earth Link	Maximum Total Link
15	0.82 Mbps	4.80 Mbps	12.30 Mbps	71.99 Mbps	74.00 Mbps	444 Mbps	12.30 Mbps

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Coverage Analysis

The coarse study yielded the following results for continuous, complete coverage of the surface of Mars as specified by Requirement 3. The results are presented graphically in Figure 15.

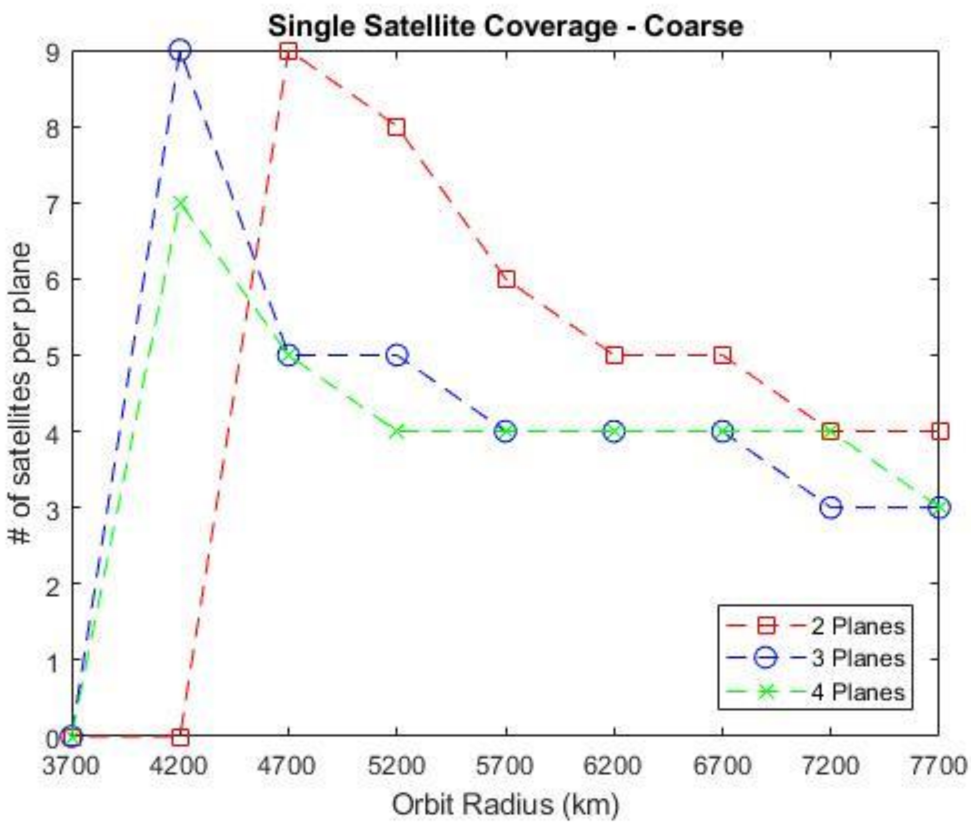

Figure 15: Coarse Study Single Satellite Coverage Results

Single satellite coverage is used to indicate that, for any grid location on the surface of Mars, at least one CubeSat is visible at all times. Each point on the graph, for a given number of planes, represents the minimum number of spacecraft needed to satisfy the single satellite coverage requirement at that orbital radius. When the minimum number of spacecraft is zero, this indicates that the 99% coverage requirement could not be met even with the maximum number of spacecraft per plane (9 in the case of the coarse study). For a given orbital radius, using fewer planes always requires the same or greater number of spacecraft per plane to meet the 99% coverage requirement, except for the 3 vs 4 plane case at 7200 km. This exception does not have an apparent physical cause and is therefore likely to be an artifact resulting from insufficient simulation fidelity. As the orbit radius increases, the number of spacecraft necessary to achieve the coverage requirement decreases regardless of the number of planes, which is consistent with common sense orbital mechanics (higher altitude correlates with wider field of view). The set of possible configurations identified by the coarse study are given in Table 10.

Table 10: Possible Configurations Identified from Coarse Study

Number of Spacecraft per Plane		Orbital Radius (km)								
		3700	4200	4700	5200	5700	6200	6700	7200	7700
Number of Planes	2	X	X	9	8	6	5	5	4	4
	3	X	9	5	5	4	4	4	3	3
	4	X	7	5	4	4	4	4	4	3

As can be seen, a minimum of two additional spacecraft for a four plane constellation are required for the radius decrease from 4700 to 4200 km. Additionally, for a three plane constellation, a minimum of four spacecraft are required for the same radius decrease. This indicates that the necessary number of satellites is highly sensitive to changes to orbital radius when the radius is low (at 4700 km and below). Therefore, finer resolution is needed to adequately capture the solution space in this region. It is also worth noting that the coarse study was capped at nine spacecraft per plane, as discussed in section 3.1, which may have led to the lack of identified configurations at 3700 km. As a result, configurations at low orbital radii (between 3700 and 4700 km) are not adequately captured by the coarse study. The need for more possible spacecraft per plane and finer resolution motivates the input parameters used in the fine study, given in Section 3.1.

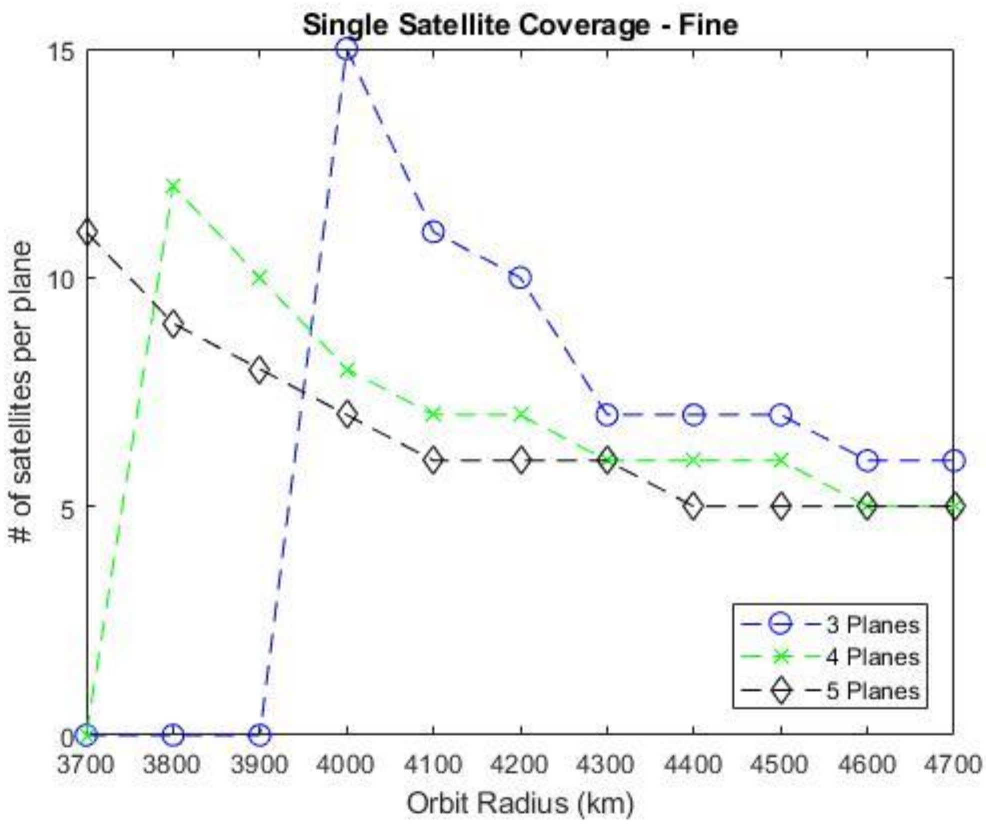

Figure 16: Fine Study Single Satellite Coverage Results

The fine study results are presented in Figure 16, with trends similar to those from the coarse study. The number of spacecraft necessary to achieve single satellite coverage decreased continuously as the orbit radius was increased. In all cases, the number of spacecraft required per plane at a given orbital radius decreased or remained constant as the number of planes was increased. It is worth noting that the gap in necessary spacecraft per plane is larger between the 3 and 4 plane cases than the 4 and 5 plane cases. This is due to the lower decrease in the RAAN spread between the 3 and 4 plane case (120 to 90 degrees) than between the 4 and 5 plane case (90 to 72 degrees). The set of possible configurations identified in the fine study are given in Table 11.

Table 11: Possible Configurations Identified from Fine Study

Number of Spacecraft per Plane		Orbital Radius (km)										
		3700	3800	3900	4000	4100	4200	4300	4400	4500	4600	4700
Number of Planes	3	X	X	X	15	11	10	7	7	7	6	5
	4	X	12	10	8	7	7	6	6	6	5	5
	5	11	9	8	7	6	6	6	5	5	5	5

4.2 Stability Analysis

Stability analysis was conducted to determine the stability of all constellation configurations identified by the coverage analysis and presented in Tables 10 and 11. First, CubeSats in single orbits at each identified orbital radius were simulated to determine inclination and semi-major axis stability for the constellations at those radii. These orbits were subjected to the perturbation effects of non-sphericity and SRP at all radii, as well as atmospheric drag for orbits with radii less than 4200 km. While simulating these single orbits, it was determined that atmospheric drag caused the CubeSat in a 3700 km radius orbit to decay and impact the Martian surface after approximately 20 months. As a result, constellation configurations at this radius were removed from consideration. All spacecraft with initial orbital radii of 3800 km and above did not substantially decay during the 10-year timespan.

Table 12: Effect of Perturbations on Semi-Major Axis Variation

Initial Radius (km)	3800	4200	4700	5700	6700	7700
Maximum Variation of Semi-Major Axis (km)	-17.89	-16.24	-14.5	-11.88	-10.12	-8.83
Average Variation of Semi-Major Axis (km)	-8.14	-7.38	-6.61	-5.45	-4.64	-4.03

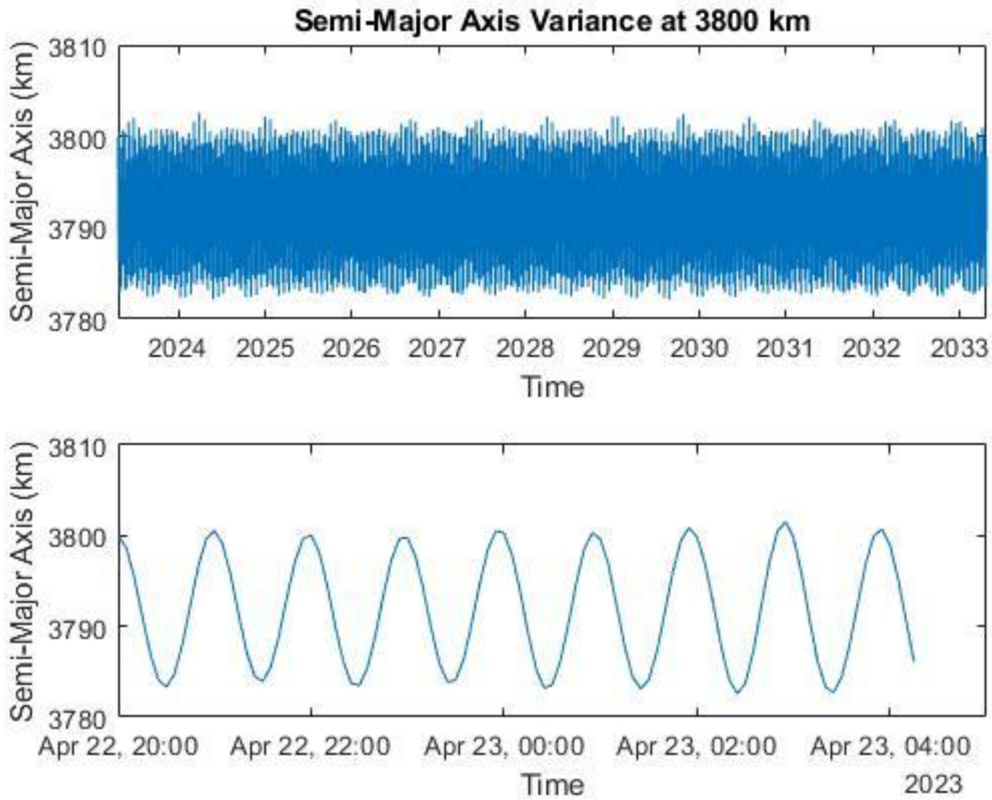

Figure 17: Semi-Major Axis Variance at 3800 km Radius

The effect of the perturbations on the semi-major axis was consistent for all radii in terms of the perturbation pattern, although the scale of the perturbation effect decreases significantly with the orbital radius. Table 12 gives the maximum and average variation of the semi-major axis for a representative selection of the considered radii. At all radii, the semi-major axis has a mean value within 20 km of its original value, with the maximum variance equal to approximately twice the magnitude of the mean variance. The perturbation pattern is shown in Figure 17 for the 3800 km radius case, where the perturbation's effect is most pronounced. The average value of the semi-major axis is slightly reduced to about 3792 km, with significant short-period (similar to the orbital period) oscillations. As the semi-major axis only experiences symmetrical, short-term fluctuations, the average value of the semi-major axis is nearly constant throughout the ten-year duration. Given its near constancy and proximity to its initial value at all radii, all constellation configurations can be considered stable in terms of the semi-major axis.

Table 13: Effect of Perturbations on Inclination Variance at Multiple Radii

Initial Radius (km)	3800	4200	4700	5700	6700	7700
Maximum Variation of Inclination (deg)	0.091	0.063	0.046	-0.037	-0.041	-0.048
Average Variation of Inclination (deg)	0.023	0.0124	0.0044	-0.0055	-0.011	-0.01

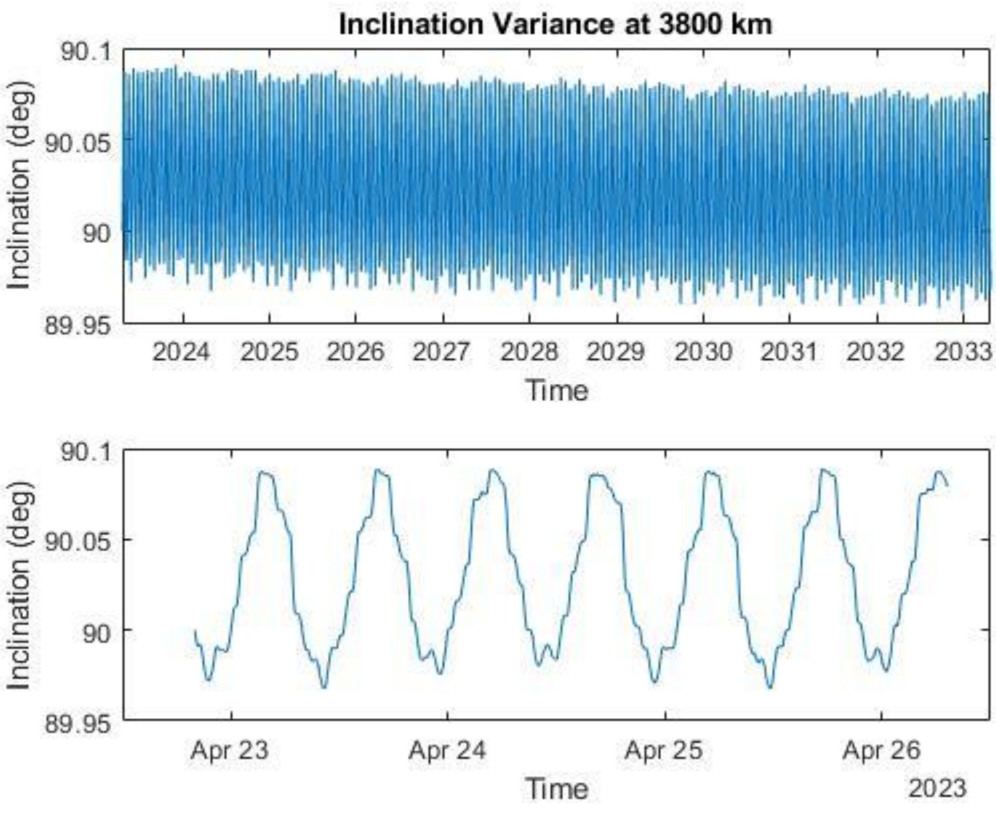

Figure 18: Inclination Variance at 3800 km Radius

The effect of the perturbations on the inclination of the orbit was consistent across all radii, with scale decreasing with increased radius. The mean and maximum variance of the inclination is given in Table 13. At all radii, the average inclination is within 0.25 degrees of its initial value, with less than 0.1 degrees maximum variance. The inclination variance at 3800 km radius, where the perturbation's effect is strongest, is given in Figure 18. There are no long term oscillations, but the inclination does slightly decrease over the 10 year lifespan. Short term oscillations appear to have a period equal to roughly half of a sol, and are symmetric in nature. Due to the stability of the inclination over time, and the proximity of the perturbed to the starting value, all constellation configurations can be considered stable in terms of inclination.

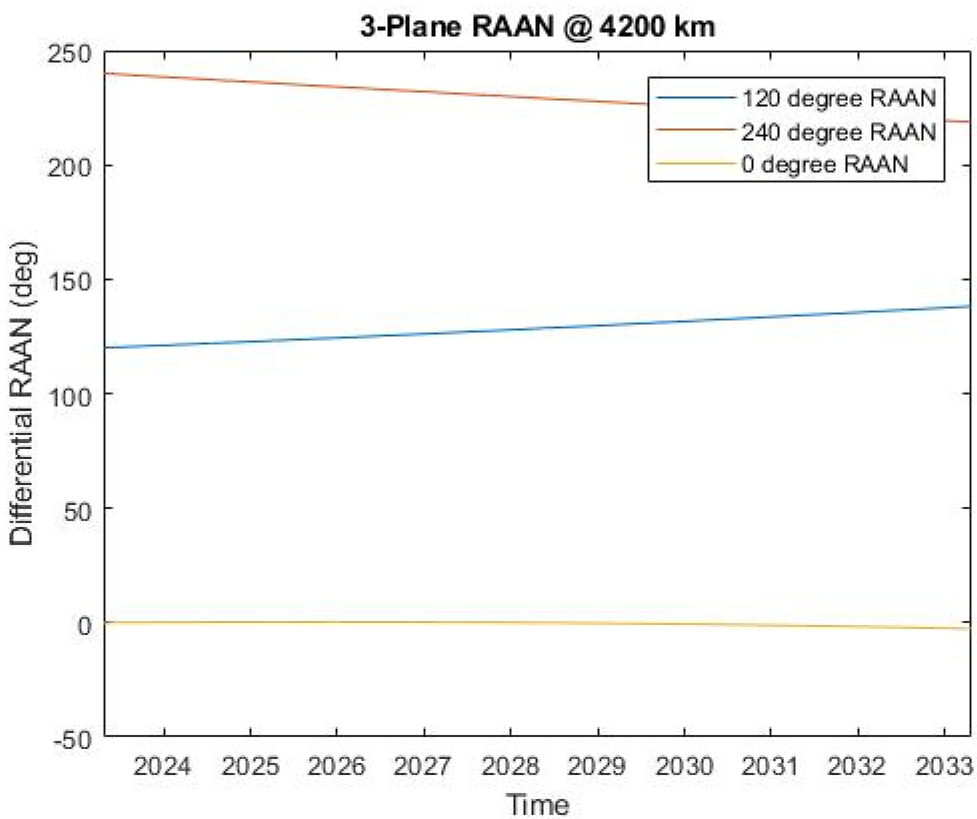

Figure 19: RAAN Spread for 3-Plane, 4200 km Radius Case

The remaining stability element to be investigated is the constellation's RAAN spread, shown in Figure 19 for the 4200 km case. The RAAN rate was not consistently greater at lower radii, so a representative case at 4200 km is given. The RAAN rate was expected to be virtually zero, since the non-sphericity perturbation is dominant and the initial orbit had a 90 degree inclination. Equation 8 describes the RAAN rate resulting from the J2 term, the dominant term of the spherical harmonic equation that describes the non-sphericity perturbation effects. The terms inside the bracket are very nearly constant, so the magnitude and direction of the RAAN rate are dictated by the cos(inc) term. Since the initial inclination of all orbits considered is 90 degrees, a RAAN rate of zero or nearly zero was expected, yet for both the 120 and 240 degree initial RAAN cases, the RAAN either increases or decreases at a substantial rate, as shown in Figure 20.

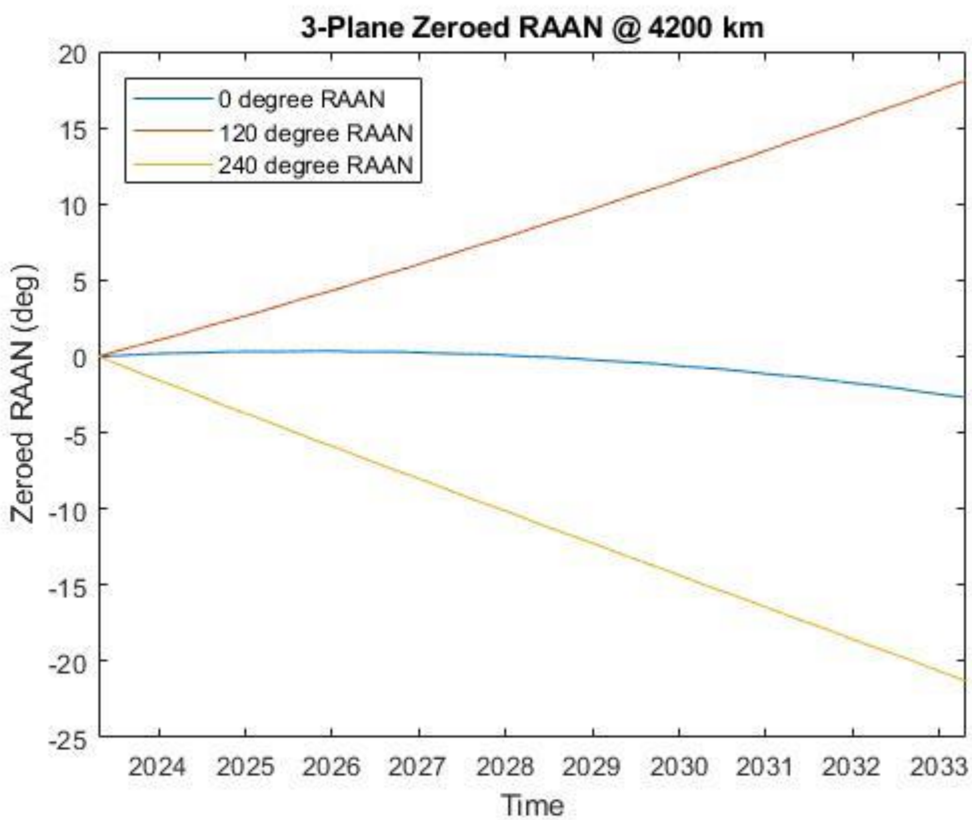

Figure 20: Zeroed RAAN Spread for 3-Plane, 4200 km Radius Case

This causes the inter-plane spacing of the constellation to change over time, which can result in loss of coverage. In this example, the maximum inter-plane RAAN gap would increase from 120 to about 128 degrees after 35 months, and then to about 140 degrees after 10 years. This change in constellation geometry is likely to result in a loss of coverage in some portion of this exposed swath, and must therefore be mitigated.

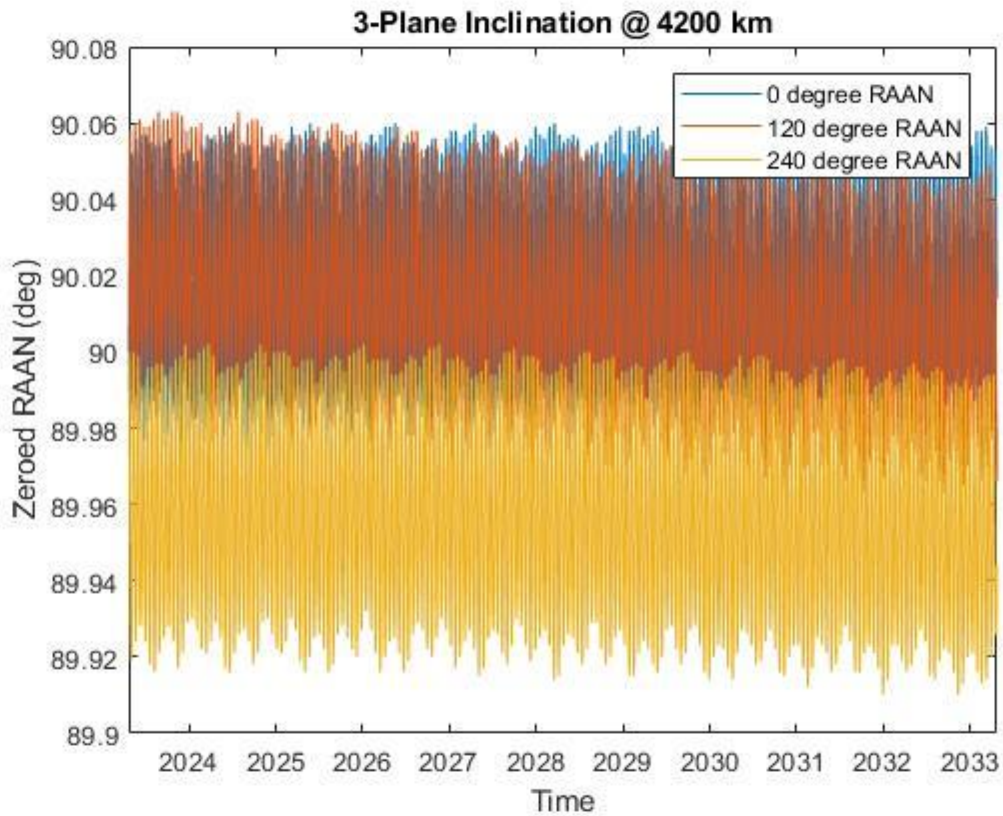

Figure 21: Inclination of Orbits in 3-Plane 4200 km Radius Case

The root cause of the varying RAAN rate appears to be the inclination of each orbit. The inclinations of the three CubeSats simulated in the 3-Plane, 4200 km case, shown in Figure 21, appear to loosely correlate with the RAAN rates shown in Figure 17. However, the effects of the higher order terms (up to degree and order 20) simulated by STK make this correlation hazy. By using MATLAB to isolate the J2 term and increasing the radius to 4700 km, the relationship is clarified. As can be seen in Figure 22, the average inclination for each orbit, about 89.975, 90.000, and 90.025 for the initial RAAN values of 0, 120, and 240 degrees, respectively, correlates precisely with the observed RAAN rate for each satellite. While these inclination variances are very small, they have significant effects on the RAAN precession rate due to the cosine term in Equation 8. Due to the sensitivity of this term, it is expected that the varying RAAN rates can be controlled by leveraging the J2 term with slight inclination adjustments. Design and analysis of such a control scheme was deemed out of scope for this thesis, due to the complexity inherent to control system design and the author's lack of expertise in the field.

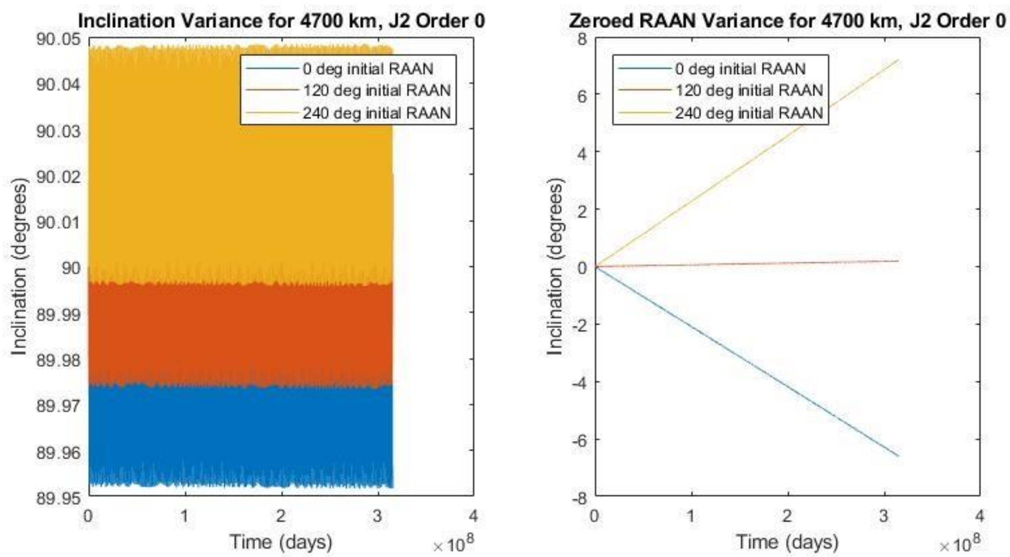

Figure 22: Effect of J2 Perturbation on Inclination and RAAN Rate at 4700 km

$$\dot{\Omega} = -\left[\frac{3 * J2 * {R_M}^2 * \sqrt{\mu}}{2 * (1 - e^2)^2 * a^{7/2}}\right] * \cos(inc)$$

Equation 8: RAAN Rate due to J2 [22]

4.3 Link Analysis

Link budget analysis was conducted for each possible link identified in Section 2.5 and discussed in Section 3.3. For each link, the variable parameters are identified, traded, and discussed, with two goals in mind: Identification of the maximum performance configuration for each link in each constellation configuration, and mapping of the design space so that communication elements can be designed to match the necessary performance requirement on a per-link basis. For all link segments, the uplink requirement (Requirement 2) was easily met, as will be shown at the end of this section. The downlink requirement (Requirement 1) was found to be the design driver, and is analyzed in detail for each link segment.

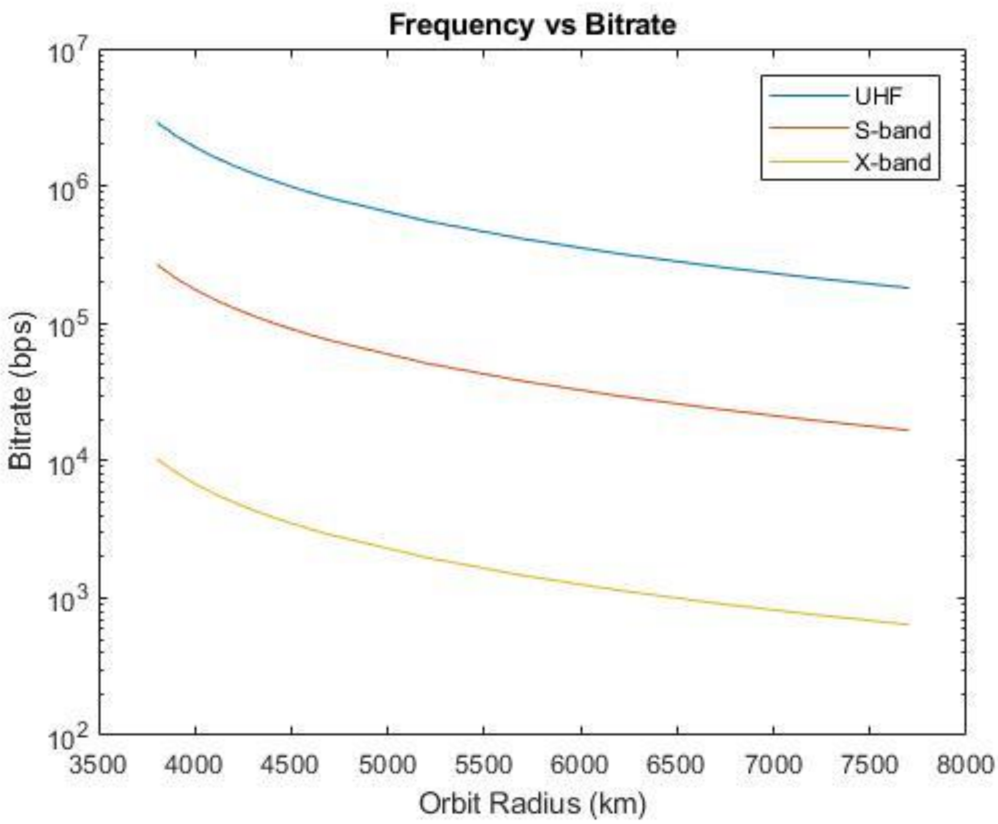

Figure 23: Link 1 Frequency vs Bitrate at Various Orbital Radii

For Link 1, between a CubeSat in Martian orbit and a spacecraft on the Martian surface, the first variable parameter to be analyzed is the frequency used. Only UHF, S-band, and X-band frequencies were analyzed, assuming 10 W RF transmit power for the surface craft. For X and S-band, patch antennas with reception and transmission gains of

6 dB (X-band) and 7 dB (S-band) were assumed as per their commercially available parts' datasheet [42], [43]. For UHF, a quarter-length monopole antenna with a reception and transmission gain of 5.2 dB was assumed as the resulting gain and antenna pattern were the closest match available to the patch antennas used for X and S band [40]. The communications path was set as the worst case distance between the surface craft and the CubeSat, calculated trigonometrically. The results are shown in Figure 23. Regardless of the considered orbital radius of the CubeSat, UHF offers the highest bitrate due to the lower path loss at this frequency, as calculated by Equation 7. While the use of UHF typically does not lead to higher overall data rates due to the loss of gain resulting from the decreased frequency (as would occur with parabolic antennas using Equation 2), the fact that different antennas are used for each frequency (patch antennas for S and X-band, quarter-length monopole for UHF) removes this factor from the analysis. The UHF line on Figure 23, therefore, represents the best performing configuration for the downlink portion of Link 1.

For Link 2, between a CubeSat in Martian orbit and a ground station on Earth, assumed to be equivalent to a 34-m DSN station, the first variable parameter to be analyzed was the transmit frequency. Due to CubeSat SWaP limitations, as previously described in Section 2.5, only transmit powers from 1 to 10 W RF were used, with a maximum parabolic antenna diameter of 0.5 m. The results are given in Figure 24. The analysis shows that the maximum achievable data rate with the available power, antenna, and frequencies is 12.4 kbps, about three orders of magnitude lower than the 11.3 Mbps specified by Requirement 1. This implies that, to meet the requirement, about 1000 CubeSats in continuous communication with Earth would be necessary. For this reason, using a direct link between the CubeSats and Earth was deemed not feasible with current technology; the use of Relay spacecraft is justified and further investigated, as mentioned in Section 2.5.

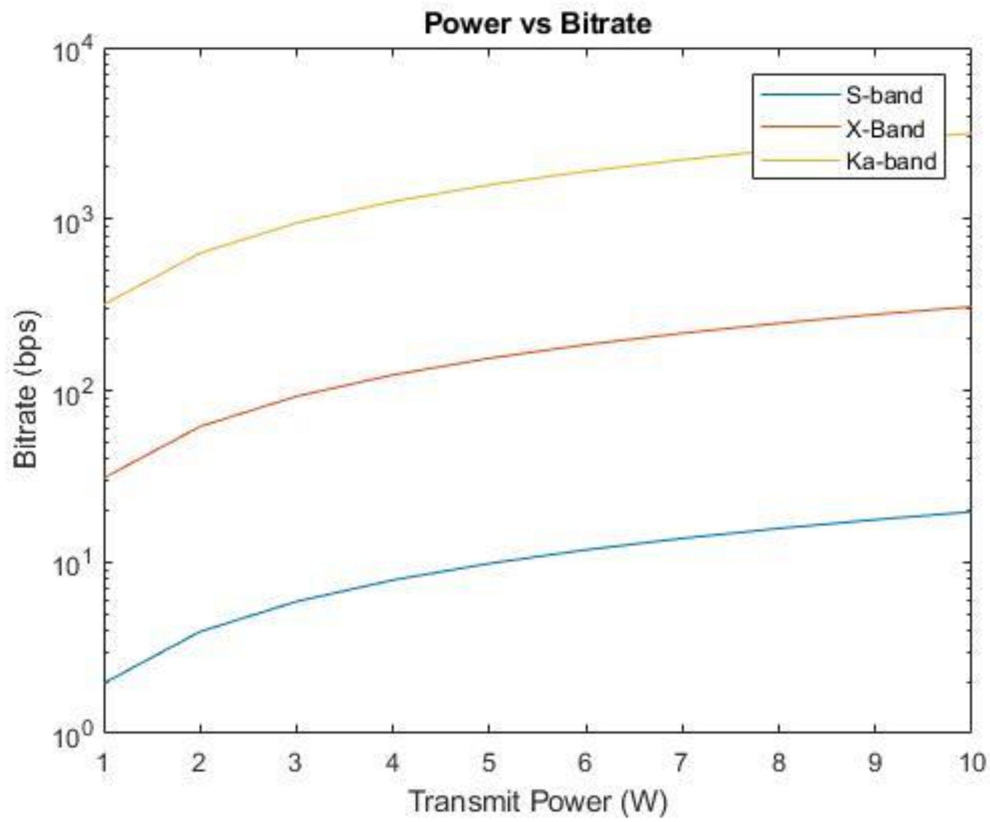

Figure 24: Link 2 Transmit Power vs Bitrate for Various Frequencies

By replacing the CubeSat in the CubeSat to Earth link with the larger Relay spacecraft, resulting in Link 4, larger parabolic antennas and higher transmit powers can be used due to the larger SWaP margins when compared with CubeSats. Northrup Grumman Astro offers the commercially available high-frequency antennas with diameters up to 22 meters [48]. Therefore, antennas up to and including this size are considered in the analysis. The first variable parameter to be traded for Link 4 is the frequency used. A 100 W transmit power is assumed and the results are given in Figure 25. The increase in antenna gain offered by use of Ka-band overwhelms the increase in attenuation loss, resulting in an increase in bitrate of roughly an order of magnitude compared to X-band in this case. With the antennas considered all supporting Ka-band communication, this frequency is the clear choice for the relay spacecraft for use on Link 4. With Ka-band assumed for the relay, dish size and transmit power, assumed to be capped at 150 W RF, are compared against bit rate in Figure 26.

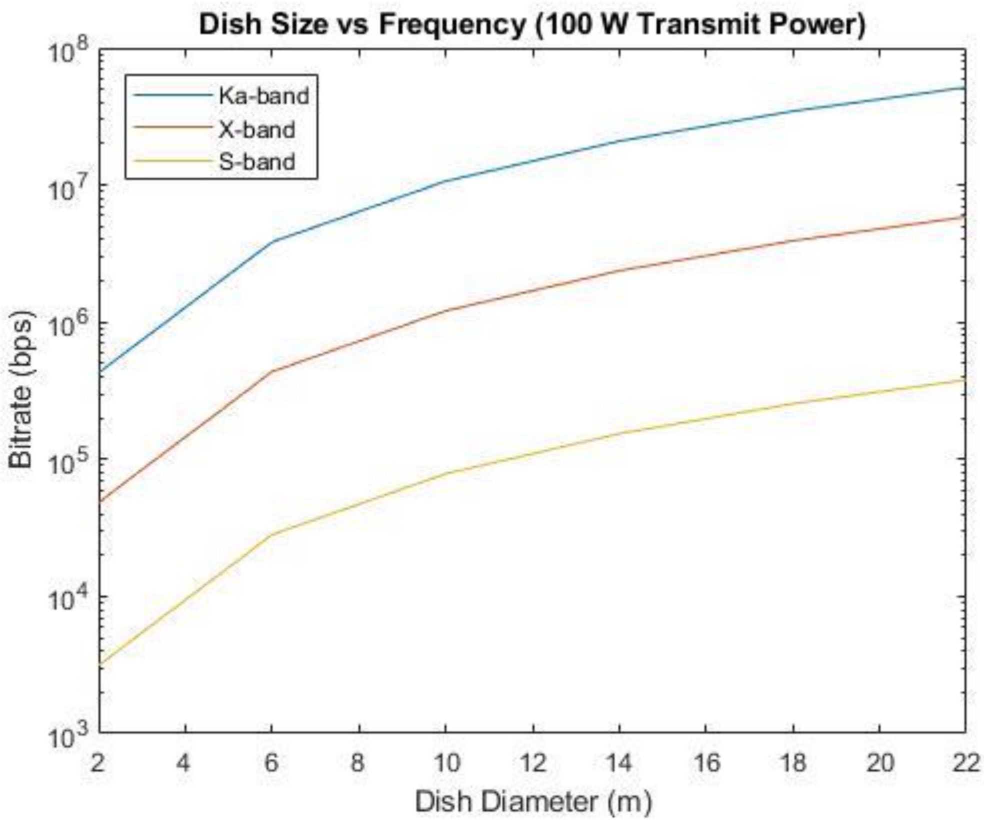

Figure 25: Link 4 Earth-Facing Dish Size vs Bitrate at Various Frequencies

Increasing relay antenna diameter increases data rate, as expected. With the largest antenna offered, and at the maximum transmit power of 150 W RF, bit rates of up to 74 Mbps are shown to be achievable. This far exceeds the required value, 11.3 Mbps, which is met by the 10m dish at 120 W RF. Antenna size will need to be traded with transmit power to find a reasonable combination of the two values if the downlink requirement were to be changed.

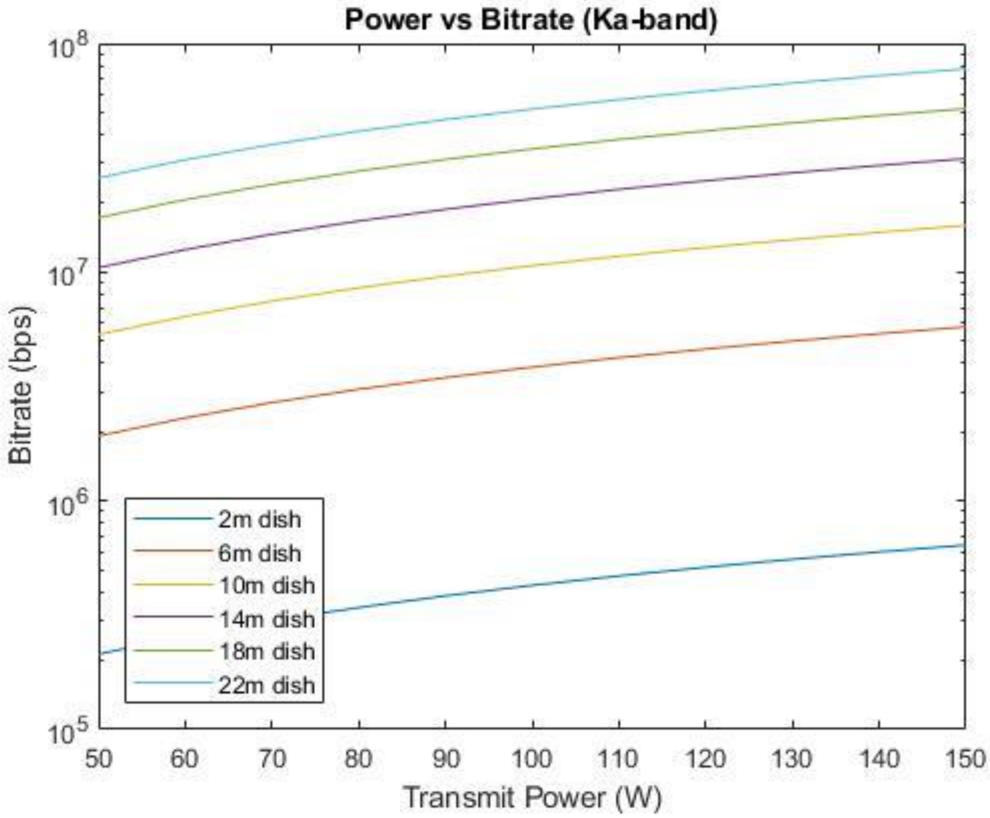

Figure 26: Link 4 Transmit Power vs Bitrate with Variable Antenna Diameter

For Link 3, CubeSat to Relay spacecraft, the first variable parameter to be investigated is the frequency used, since frequency selection has yielded a clear top performing option in each case. For this study, the orbital radius of the relay spacecraft, was calculated to keep the entire CubeSat constellation within the half-power beamwidth of the relay antenna, according to Equation 9.

$$\theta = 21/(f * d)$$

Equation 9: Half Power Beamwidth Equation

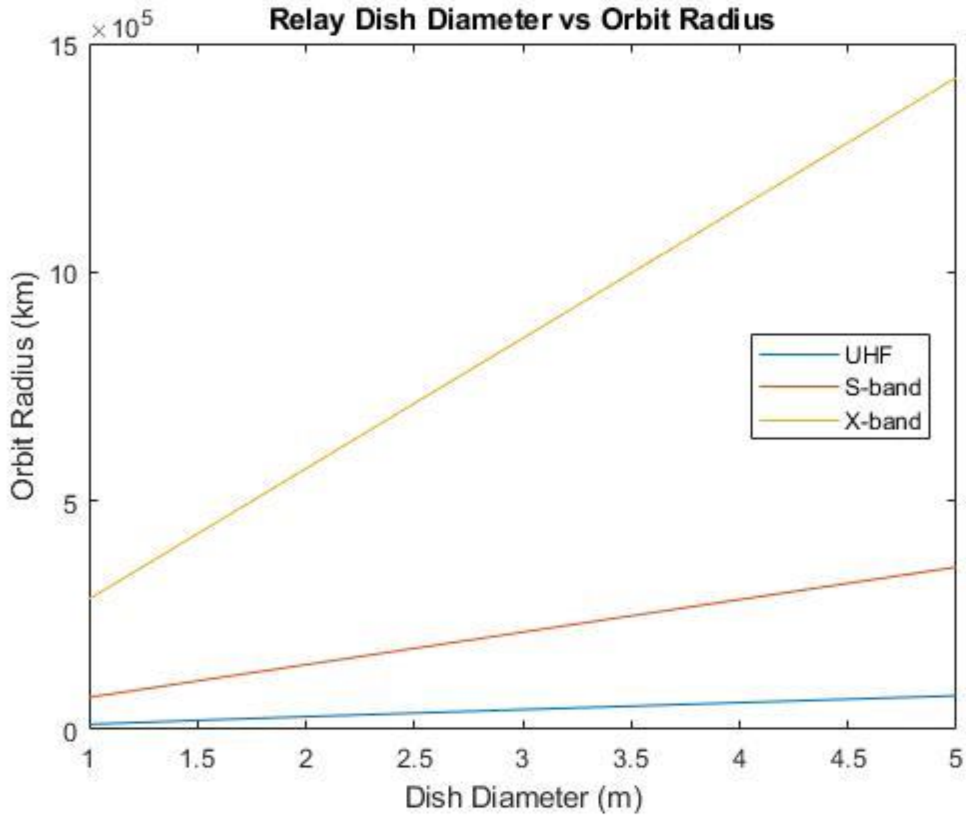

Figure 27: Link 3 Mars-Facing Relay Antenna Diameter vs Relay Orbital Radius

This method was chosen to ensure that the Relay spacecraft antenna would have reception or transmission gain within 3 dB of the peak antenna gain regardless of which CubeSat in the constellation the Relay was communicating with. The relationship between orbital radius and antenna diameter is linear for all frequencies, as shown for CubeSats in 6200 km radius orbits in Figure 27. Unfortunately, this method also requires a large orbital radius for the Relay, which ultimately results in a low maximum data rate (0.27 Mbps for UHF), as shown in Figure 28. The data rate is nearly invariant across all constellation radii, so it was concluded that this method of positioning the Relay and sizing its antenna was insufficient for Link 3 to meet the downlink data rate requirement (Requirement 1).

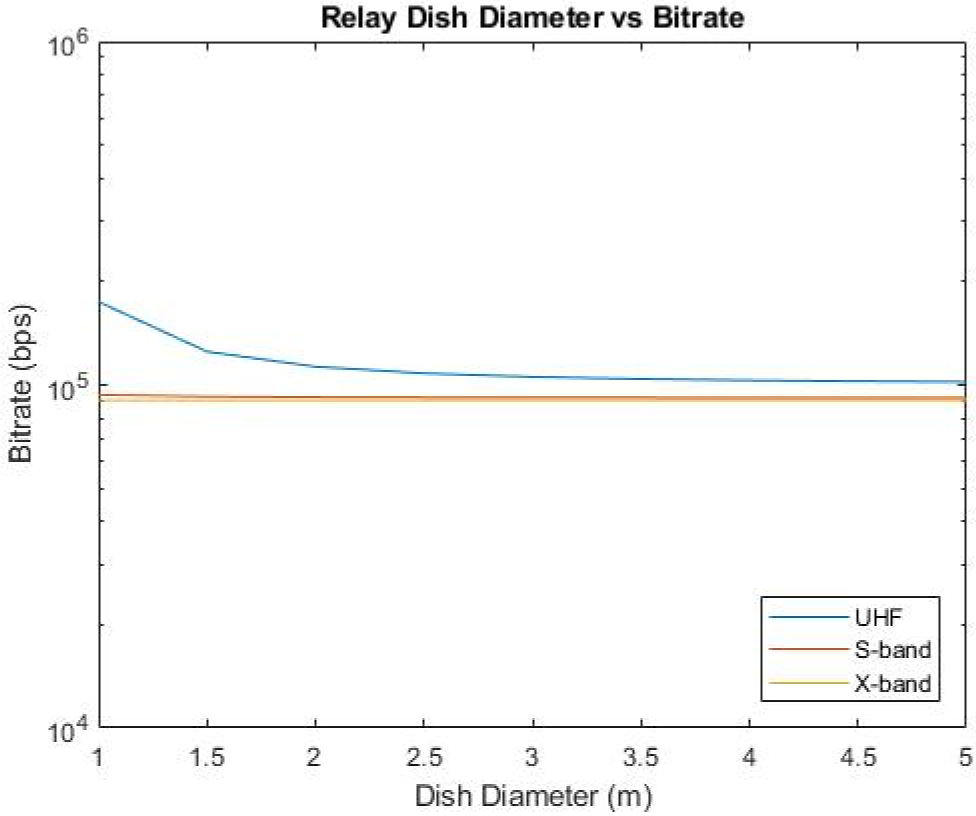

Figure 28: Link 3 Mars-Facing Relay Dish Diameter vs Bitrate at Various Frequencies

To improve the performance of Link 3, shaped antennas were used and Relay spacecraft were assigned to only cover one plane of the constellation, as shown in Figure 29. To determine the orbital radius of the Relay, the synodic period was fixed to a maximum of one sol, so that the geometry of the CubeSats and Relay for each plane would reset after a one sol period or shorter. The periods of the CubeSats were first calculated using Equation 10, where a (m) is the semi-major axis of the orbit and μ (m^3s^{-2}) is the standard gravitational parameter of Mars (4.282×10^{13}). The necessary period of the Relay was then calculated using Equation 11, where P_1 is the period of the CubeSat, P_2 is the period of the Relay, and P_S is the synodic period of the CubeSat-Relay system (defined as 1 sol). P_1, P_2, and P_S all have the same units of time. From the Relay period, the semi-major axis of the Relay was backed out using Equation 10.

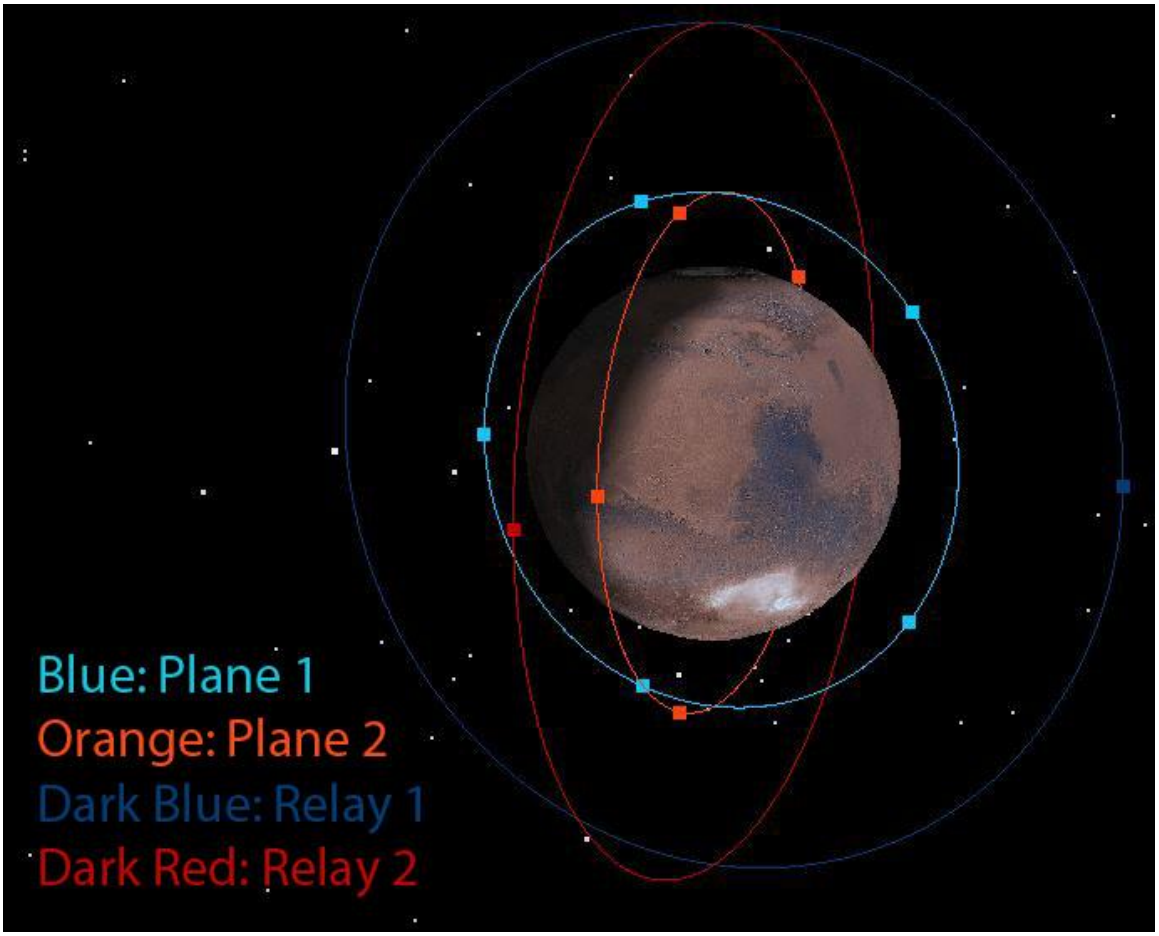

Figure 29: Allocation of Relay Satellites to CubeSat Orbital Planes

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

Equation 10: Calculation of Orbital Period

$$P_S = \frac{1}{\left|\frac{1}{P_1} - \frac{1}{P_2}\right|}$$

Equation 11: Synodic Period Equation

To ensure that all CubeSats in a plane could be continuously covered by a maximum of two Relay satellites, the eclipse angles of the CubeSats were calculated trigonometrically. For those configurations where eclipse angles were greater than 180 degrees, the Relay radius was increased until the eclipse angle was equal to 180 degrees. To account for inconsistencies on the Martian surface, the radius of Mars used to compute eclipse angles was increased from the true value of 3390 km to 3490 km. The resulting Relay radii are given in Appendix C. To account for the varying distance between the CubeSat and Relay spacecraft, the free path loss equation was integrated over the range of distances experienced during each synodic period. These average free path losses are also given in Appendix C.

$$G = 10log\left(\frac{41253}{A_\theta}\right) - 10log(\eta)$$

Equation 12: Shaped Antenna Gain

The gain of the shaped antennas were calculated from the necessary coverage area A_θ (deg^2) and dimensionless antenna efficiency η using Equation 12. Antenna efficiency was conservatively assumed to be 0.5. To determine the necessary coverage area, trigonometry was employed to calculate the angle between the two edges of the CubeSat plane and the Relay satellite. The cross-track coverage angle was calculated so as to keep the dimensions of the shaped antenna below five m, as estimated by the half-power beamwidth equation (Equation 9). The resulting estimated Relay antenna and beam pattern dimensions can be found in Appendix C.

With the Relay position and antenna configuration defined, the variable parameters to be analyzed are frequency and transmit power. The frequencies considered are UHF, S-band, and X-band. Figure 30 shows the data rate achieved by each frequency over the given range of CubeSat radii, assuming 10 W RF transmit power. As can be seen, UHF offers the best data rate performance, with the additional advantage of allowing the CubeSats to use the same frequency for both Links 1 and 3. With UHF selected, the transmit power of the CubeSats is varied from one to 10 W RF, and the results are given in Appendix D. The transmit power used by the CubeSats will need to be selected so as to balance the data rate achieved by each link element, as will be discussed in Section 4.4.

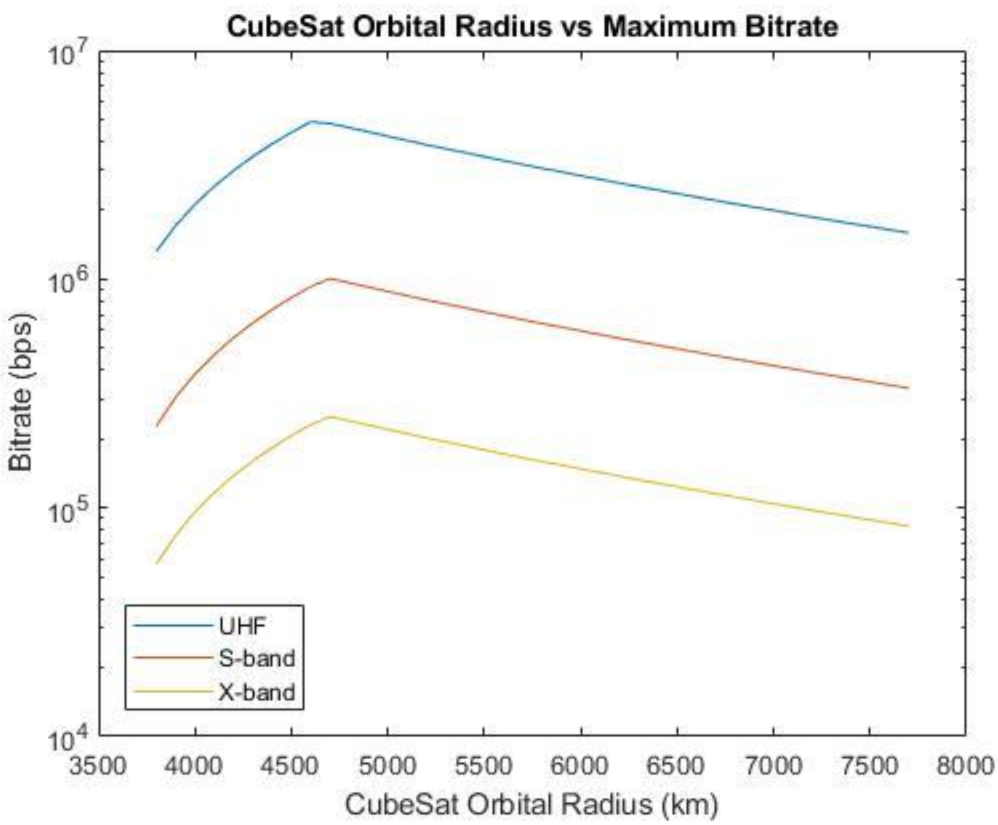

Figure 30: Link 3 Shaped Antenna Bitrates vs CubeSat Orbital Radius at Various Frequencies

Based on the link element results, a configuration implementing one or more relay satellites is recommended. UHF is selected as the operating frequency for Links 1 and 3, and Ka-band is selected for Link 4. Link 2 is unused. A full table of possible hardware configurations and their corresponding data rates for each link in both the uplink and downlink directions is provided in Appendix D.

4.4 Architecture Analysis

By combining the results of the coverage, stability, and link budget analyses conducted in Sections 4.1-4.3, all key performance parameters relevant to the four stakeholder requirements have been identified. The coverage analysis generated the WDP constellations defined in Tables 10 and 11. The stability analysis found that the 3700 km radius, 5 plane configuration identified was unstable and must be discarded, as atmospheric drag caused Cubesats at this radius to crash into the surface of Mars before the 35 month minimum operational lifetime had elapsed. All other constellations were found to be stable, provided small orbital correction maneuvers could be performed. The link budget analysis determined the maximum data rates achievable in both the uplink and downlink directions for each link segment for all orbital radii of the identified constellations. This information is synthesized completely in Appendix B and as an Excel spreadsheet in Supplemental Material A.

To select the optimal architecture from the constellations identified, the stakeholder requirements must be reconsidered. Since all remaining constellations passed the coverage and stability analyses, all remaining configurations also meet Requirements 3 and 4. By inspection of the uplink data rates in Appendix B, it can be verified that all remaining constellations pass Requirement 2. The total downlink data rates, assuming that Links 1 and 3 are used at capacity at all times (this gross assumption will be revisited in section 5.1) and that Link 4 is used at capacity when not in eclipse, are presented in

Tables 14 and 15 for the remaining constellations. Since Requirement 1 specifies that the total downlink capability must be at least 11.3 Mbps, some of the high orbital radius constellations from the coarse study must be removed from consideration, as their downlink capability is insufficient. These configurations are marked in red, leaving 33 configurations that meet the stakeholder requirements.

Table 14: Total Downlink Data Rates for Constellations Identified in the Coarse Study

Total Downlink Data Rate (Mbps)		Orbital Radius (km)								
		3700	4200	4700	5200	5700	6200	6700	7200	7700
Number of Planes	2	X	X	14.8	9.0	4.9	3.2	2.6	1.7	1.4
	3	X	42	12.3	8.4	4.9	3.8	3.1	1.9	1.6
	4	X	39.2	16.4	9.0	6.6	5.1	4.2	3.4	2.2

Table 15: Total Downlink Data Rates for Constellations Identified in the Fine Study

Total Downlink Data Rate (Mbps)		Orbital Radius (km)										
		3700	3800	3900	4000	4100	4200	4300	4400	4500	4600	4700
Number of Planes	3	X	X	X	82.5	53.5	42.0	25.8	23.1	20.8	16.0	12.3
	4	X	52.2	58.1	58.7	45.4	39.2	29.5	26.4	23.8	17.8	16.4
	5	X	48.9	58.1	64.2	48.6	42.0	26.9	27.5	24.8	22.3	20.5

For these configurations, the method of trade studies will be employed to select the optimal configuration. As outlined in Section 3.4, the key parameters associated with the cost of flying the constellation are the total number of satellites and the number of planes those satellites occupy. The total number of satellites for each configuration are given in Tables 16 and 17. As can be seen, the 2 plane, 4700 km radius configuration minimizes plane count, and is nearly minimal for satellite count (3 more than the lowest). If it is assumed that additional link capacity is both unnecessary and incapable of offsetting the cost of additional CubeSats or planes, this results in this configuration becoming the selected configuration for precisely meeting the given stakeholder requirements.

Table 17: Total Number of Satellites for Constellations Identified in the Coarse Study

Total Number of Satellites		Orbital Radius (km)								
		3700	4200	4700	5200	5700	6200	6700	7200	7700
Number of Planes	2	X	X	18	16	12	10	10	8	8
	3	X	30	15	15	12	12	12	9	9
	4	X	28	20	16	16	16	16	16	12

Table 16: Total Number of Satellites for Constellations Identified in the Fine Study

Total Number of Satellites		Orbital Radius (km)										
		3700	3800	3900	4000	4100	4200	4300	4400	4500	4600	4700
Number of Planes	3	X	X	X	45	33	30	21	21	21	18	15
	4	X	48	40	32	28	28	24	24	24	20	20
	5	X	45	40	35	30	30	30	25	25	25	25

To complete the description of the selected configuration, a few more parameters must be specified. The communications hardware for each spacecraft must be defined, and the number of Relay satellites must be determined. By examination of Appendix B, Link 1 is identified as the link segment with the lowest data-rate, 0.82 Mbps, so the other three links can be downscaled to reduce their cost. Referencing Appendix D shows that, by setting the CubeSat transmit power to 4 W RF, a data rate of 1.06 Mbps is achieved for Link 3, well in excess of the 0.82 Mbps offered by Link 1. For Link 4, four Relay satellites are assumed, so as to ensure all CubeSats have a Relay link available at all times. Selecting a dish size of six m and a transmit power of 120 W RF yields a data rate of 4.4 Mbps, or 2.93 Mbps after accounting for Martian eclipses. Taking the four relays together, this results in a combined downlink data rate of 11.7 Mbps. In the uplink direction, selecting a transmit power of 1 W RF for the Relays and for the CubeSats results in data rates of 400 and 140 kbps, respectively. The parameters of this chosen architecture are summarized in Table 18 and the architecture is presented graphically in Figure 31.

Table 18: Recommended Configuration Parameters

<table>
<tr><td rowspan="4">CubeSats:</td><td>Orbital Radius</td><td># of Planes</td><td># of Satellites Per Plane</td></tr>
<tr><td>4700 km</td><td>2</td><td>9</td></tr>
<tr><td>Antennas</td><td colspan="2">Transmitters</td></tr>
<tr><td>2 x UHF 1/4-length monopole antenna</td><td colspan="2">4 W RF UHF Transmitter (downlink)
1 W RF UHF Transmitter (uplink)</td></tr>
<tr><td rowspan="4">Relays:</td><td>Orbital Radius</td><td># of Planes</td><td># of Relays Per Plane</td></tr>
<tr><td>5996 km</td><td>2</td><td>2</td></tr>
<tr><td>Antennas</td><td colspan="2">Transmitters</td></tr>
<tr><td>6-m Earth-facing dish
0.34 x 5-m Mars-facing antenna</td><td colspan="2">50 W RF Ka-band Transmitter (downlink)
1 W RF UHF Transmitter (uplink)</td></tr>
<tr><td colspan="2">Downlink Data Rate (Constellation)</td><td colspan="2">Uplink Data Rate (per Surface Craft)</td></tr>
<tr><td colspan="2">11.7 Mbps</td><td colspan="2">140 kbps</td></tr>
</table>

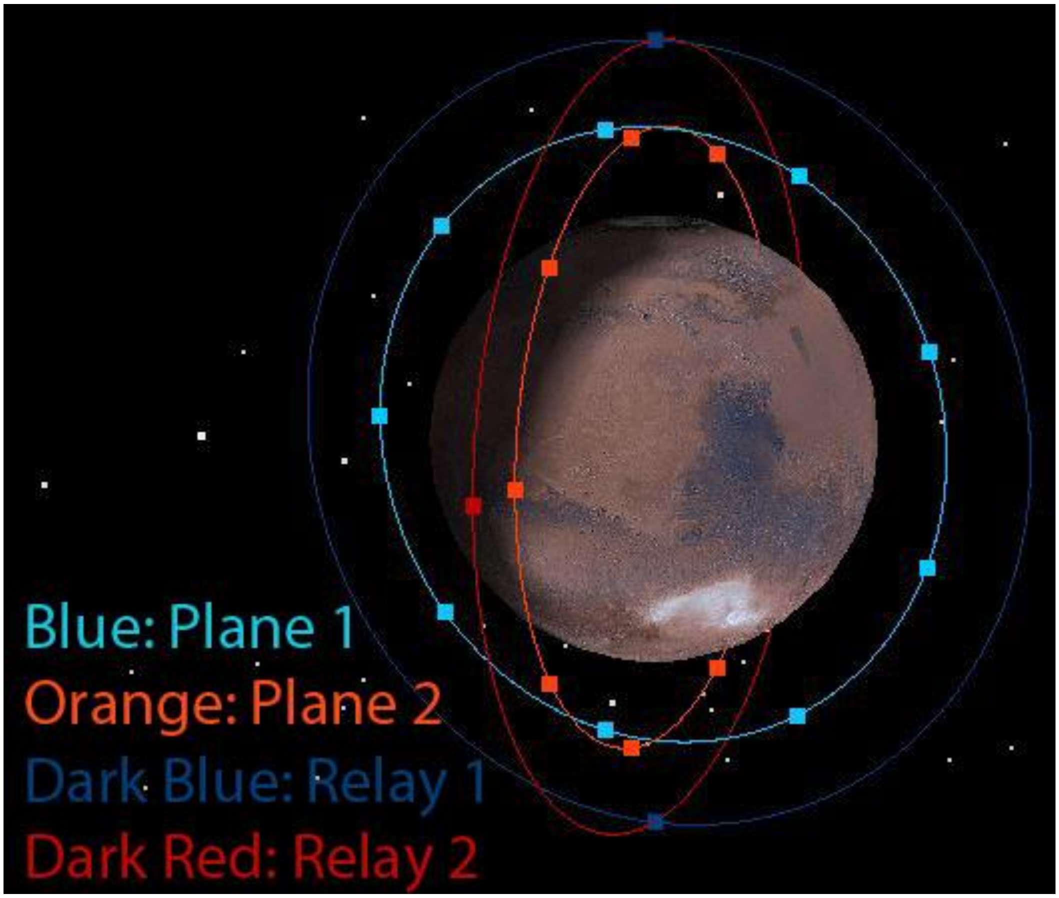

Figure 31: Recommended Architecture

CHAPTER 5

CONCLUSION

5.1 Alternate Architectures

The procedure used to generate the recommended architecture, while tailored to the stakeholder requirements originally given, can be adapted to generate architectures for a variety of different requirements. For example, the assumption made in Section 4.4, that all links are used at capacity at all times (except Link 4, for which eclipses are taken into account) is optimistic to a fault. For an alternate architecture, the assumption will now be that surface and relay links are available only 50% of the time for each CubeSat, with all stakeholder requirements remaining the same. This has the effect of requiring twice the total downlink capacity for Links 1 and 3, increased from 11.3 Mbps to 22.6 Mbps, with only one relay satellite now being used per plane. Consulting Appendix B, this requirement drastically reduces the number of possible configurations; the total number of satellites for the remaining configurations are presented in Tables 19 and 20.

Table 19: Total Number of Satellites for Constellations Identified in the Coarse Study which Meet the Alternate Data Rate Requirements

Total Number of Satellites		Orbital Radius (km)								
		3700	4200	4700	5200	5700	6200	6700	7200	7700
Number of Planes	2	X	X	X	X	X	X	X	X	X
	3	X	30	X	X	X	X	X	X	X
	4	X	28	X	X	X	X	X	X	X

Table 20: Total Number of Satellites for Constellations Identified in the Fine Study which Meet the Alternate Data Rate Requirements

Total Number of Satellites		Orbital Radius (km)										
		3700	3800	3900	4000	4100	4200	4300	4400	4500	4600	4700
Number of Planes	3	X	X	X	45	33	30	21	21	X	X	X
	4	X	48	40	32	28	28	24	24	24	X	X
	5	X	45	40	35	30	30	30	25	25	25	X

Using the same selection criteria as before (minimizing plane count and total number of satellites), the top configuration is the three plane, 4400 km radius case. After halving the total surface link and total Cube-Sat relay link, this configuration provides 11.55 Mbps total downlink capability. Upon further inspection of Appendix B, the limiting link segment is again Link 1, at 11.55 Mbps after halving. Referring to Appendix D, selecting a transmit power of 4 W RF for the CubeSat allows Link 3 to close with an average data rate of 14.7 Mbps after halving. For the Relay satellites, selecting a transmit power of 90 W RF and a dish diameter of 8 m allows Link 4 to close with an average data rate of 12.03 Mbps after accounting for eclipse. In the uplink direction, selecting a transmit power of 1 W RF for the Relays and for the CubeSats results in data rates of 175 and 110 kbps, respectively. The parameters of the resulting configuration are summarized in Table 21.

Table 21: Alternate Configuration 1 Parameters

CubeSats:	Orbital Radius	# of Planes	# of Satellites Per Plane
	4400 km	3	7
	Antennas	Transmitters	
	2 x UHF 1/4-length monopole antenna	4 W RF UHF Transmitter (downlink) 1 W RF UHF Transmitter (uplink)	
Relays:	Orbital Radius	# of Planes	# of Relays Per Plane
	5517 km	3	1
	Antennas	Transmitters	
	8-m Earth-facing dish 0.34 x 5-m Mars-facing antenna	90 W RF Ka-band Transmitter (downlink) 1 W RF UHF Transmitter (uplink)	
Downlink Data Rate (Constellation)		Uplink Data Rate (per Surface Craft)	
11.55 Mbps		110 kbps	

For another alternate study, consider that the stakeholders are planning to operate a fleet of rovers on the Martian surface, and simply want to ensure that command and control links are available at all times. Requirement 1 is modified to require 1 kbps of downlink from each CubeSat, instead of requiring 11.3 Mbps from the constellation as a whole. Returning to Appendix D, even CubeSats at the highest investigated radius, 7700 km, can close a 20 kbps link with the surface craft, assuming the surface craft is still using the 10 W RF UHF transmitter and both parties have the quarter-wavelength monopole antenna previously assumed. The requirement can be satisfied for Link 2 by implementing an 8 W RF Ka-band transmitter and a 0.5 m parabolic antenna (which is equivalent to the antenna used by the MarCO spacecraft) on each CubeSat, resulting in a data rate of 2 kbps before accounting for eclipse (less than a 50% reduction in average data rate in all cases). The configuration that minimizes both satellite and plane count is the 7700 km, 2 plane configuration with 4 CubeSats per plane. Additionally, this constellation does not need a Relay to operate, which would likely lead to a substantial reduction in program cost. After appropriately scaling the CubeSat hardware (using Appendix D as before), the parameters of the resulting configuration are summarized in Table 22.

Table 22: Alternate Configuration 2 Parameters

<table>
<tr><td rowspan="4">CubeSats:</td><td>Orbital Radius</td><td># of Planes</td><td># of Satellites Per Plane</td></tr>
<tr><td>7700 km</td><td>2</td><td>8</td></tr>
<tr><td>Antennas</td><td colspan="2">Transmitters</td></tr>
<tr><td>UHF 1/4-length monopole Mars-facing antenna
0.5-m Earth-facing parabolic antenna</td><td colspan="2">6 W RF Ka-Band Transmitter (downlink)
1 W RF UHF Transmitter (uplink)</td></tr>
<tr><td colspan="2">Downlink Data Rate (per Surface Craft)</td><td colspan="2">Uplink Data Rate (per Surface Craft)</td></tr>
<tr><td colspan="2">1.04 kbps</td><td colspan="2">20 kbps</td></tr>
</table>

Both of these studies demonstrate the flexibility of the methods used in this thesis for constellation identification, analysis, and recommendation. Slight improvements, such as adding the double satellite coverage results from Appendix C to the spreadsheet in Appendix B, would allow for architecture recommendation to stakeholders requiring redundancy in the constellation configuration. As the capabilities of CubeSats increase, the link budget analysis in Section 4.3 can be reworked with new values, allowing new constellations to be recommended for the updated hardware. Additional ideas for improving the capabilities of this architecture selection method are outlined in the following section.

5.2 Future Work

Due to the inherent complexity of the topics addressed in this thesis, many aspects of the research were limited in terms of scope. Ideas for improving the quality and depth of research conducted are presented for each of the four analysis steps: Coverage analysis (Section 4.1), stability analysis (Section 4.2), link budget analysis (Section 4.3), and architecture analysis (Sections 4.4 and 5.1). Some additional general recommendations for future work are also presented.

5.2.1 Coverage Analysis

- Constellation configurations were not searched completely for optimal solutions. Increased constellation performance in terms of data rate and cost can likely be achieved by employing optimization techniques on the design space. In particular, the use of STK's Optimizer add-on module could be used to add true optimization (instead of brute-force "optimization") to the existing constellation identification process.
- The analysis in this thesis was conducted for the fully deployed state of the constellation. Further investigation into the coverage performance of the constellation in partially deployed configurations is recommended to better understand how to best deploy the ground stations, CubeSats and Relays that comprise it.
- This thesis only analyzed constellations at an orbital radius of 7700 km and below, as the primary goal of the thesis was to develop a high data-rate architecture. As shown in Section 5.1, which identifies a requirement set that results in a 7700 km recommended architecture due to its lower data-rate requirements, some alternate requirement sets may benefit from exploration of constellations at a higher orbital radius.

- The assumptions made to facilitate the coverage calculations, namely the use of a coverage grid and approximation of the surface of Mars as smooth, could be changed to improve the accuracy of the coverage results.
- This thesis only analyzed complete, continuous, non-redundant coverage of the Martian surface. Analysis of partial or redundant coverage constellation configurations is recommended for expansion of the requirement sets that could be designed for using the techniques developed in this thesis.

5.2.2 Stability Analysis

- Stability analysis was only conducted to the extent that long term stability of the constellation as a whole could be demonstrated. Variations of true anomaly and the corresponding relative stability of spacecraft within a given plane were not analyzed. Further investigation of these effects and their mitigation would improve constellation viability.
- Stability analysis of the Relay satellites was not conducted, as it was assumed that the lack of the SWaP limitations present on CubeSats would allow for sufficient delta-V capability to make any orbital correction maneuvers that would be necessary. Stability analysis of the Relay satellites is recommended to improve the viability of the identified constellations.
- Design of orbital control schemes was not attempted by this thesis. Proper design and simulation of orbital control schemes to account for the identified RAAN drift and possible true anomaly drift is recommended to improve the viability of the identified constellations and to allow for the design of appropriate propulsion systems.

- Attitude stability analysis was not attempted by this thesis. As the antennas used throughout the link budget analysis require some degree of pointing accuracy (since they are directional antennas), stability and stability control analysis is recommended to improve constellation viability and to allow for design of appropriate attitude control systems.

5.2.3 Link Budget Analysis

- The system noise temperatures were estimated based on the low-noise amplifier gain only. Further analysis of amplification and antenna hardware is recommended to better estimate this value.
- The antenna gains for parabolic and shaped antennas were calculated from estimation equations, instead of from the design specifications of specific hardware. Further analysis and/or design of antenna hardware is recommended to improve the accuracy of these values.
- The estimated value of five dB for unconsidered losses is likely more conservative than necessary. Further investigation of the pointing and line losses, as well as improved identification of other unconsidered losses, is recommended to improve the accuracy of the link budget calculations.
- Attenuation losses were estimated as the worst-case monthly attenuation values for the DSN. Further investigation of the attenuation loss for other site locations, as well as for shorter-term (i.e. daily) worst case scenarios is recommended to improve understanding and identification of the performance and downtime potential of Link 4.

- Free space losses were either calculated as worst-case or long-term average values. Evaluation of the communication links over a continuous time domain is recommended to better understand the performance of the links and their variation with dynamic constellation geometry.
- Although not explicitly discussed in Section 4.3, some amount of store-and-forward capability is necessary for the successful operation of the constellation. Appropriate data storage sizing and further store-and-forward concept of operations development is recommended to improve the viability of the architectures.
- Calculation of necessary bandwidth and determination of bandwidth allocation procedures were not attempted by this thesis. Further link budget analysis is recommended to determine the bandwidth necessary to support the data rates identified in Section 4.3. Investigation of bandwidth allocation procedures for Martian spacecraft is also recommended to improve the viability of the architectures.
- Investigation of data block sizing and encoding hardware was not conducted by this thesis. Further analysis of these aspects of the communication system is recommended to improve the viability of the architectures.
- Investigation of necessary Relay hardware to support multiple simultaneous CubeSat-Relay links and of necessary DSN hardware to support multiple simultaneous Relay-DSN links was not conducted in this thesis. Investigation of hardware that supports this capability is recommended to improve the viability of the architectures.

5.2.4 Architecture Analysis

- Analysis of the delivery of the constellation to Mars was not conducted. Analysis of the Earth-Mars transit is recommended in particular, with an emphasis on the viability of inserting the CubeSats into each target plane. It is possible that the use of certain planes will offer different performance benefits in terms of delta-V and related deployment cost. These results will likely impact the architecture selection process.
- Further investigation of the amount of Relay spacecraft necessary per plane is recommended. The previously recommended further investigation of store-and-forward concepts of operation and their impact on performance metrics such as revisit time is likely to clarify these values.
- A detailed cost analysis of both the CubeSat and Relay spacecraft is recommended for better valuation of the number of CubeSat and number of plane metrics. As this is somewhat predicated on knowledge of the hardware to be used, such an analysis was not conducted for this thesis.

5.2.5 General Recommendations

- Analysis of appropriate hardware for the spacecraft constituting MC3 was not conducted in detail by this thesis. Further analysis is recommended for determining appropriate hardware configurations for each architecture element to improve the viability of the architectures as a whole.

- End-of-Life analysis was not conducted for the spacecraft in the MC3 constellation. Further investigation in this regard is necessary to improve the viability of the recommended mission architectures.

5.3 Lessons Learned

Throughout the process of creating this thesis, many lessons were learned that will benefit the author's future work. These are included in the hope that they may be beneficial to others as well.

- Use familiar software when possible. The time saved by easier troubleshooting can often outweigh the time saved by using more powerful software.
- Fully define the problem before attempting to solve it. While preliminary results are helpful in determining scope and direction, it is easy to overinvest time in ideas that are fundamentally flawed.
- Write up research while conducting it to the maximum extent possible. Rationales and methodology are much easier to describe in the moment than months afterward.
- Try to make arguments out loud before writing them out. It can be hard to find the right phrasing when the argument only exists on the page.
- Take advantage of any and all available expertise. The tighter the communication loop with those with more experience, the less time will be spent in fruitless directions.

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Appendix A

DECOMPOSITION OF STAKEHOLDER REQUIREMENTS

The stakeholder requirements are decomposed into the lowest system level analyzed within the thesis and presented in Table 23. The recommended architecture, as presented in Section 4.4, is assumed to be the chosen architecture.

Table 23: Decomposition of Stakeholder Requirements for Recommended Architecture

Req ID	Requirement	Rationale	Verification Technique
1	The MC3 program shall provide at least 1 Tbits/sol average total downlink capability for the Martian system	Stakeholder Requirement	Analysis
1.1	The MC3 program shall provide at least 1.18 Mbps downlink capability for craft operating on the Martian surface	Assuming at least 10 surface craft or equivalent, this leads to the satisfaction of Req 1	Analysis and test
1.1.1	The Surface-to-CubeSat link shall provide at least 1.18 Mbps data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
1.1.1.1	The surface spacecraft shall be equipped with a minimum 10 W RF transmitter	Based on results of link budget analysis	Test
1.1.1.2	The surface spacecraft shall be equipped with a minimum 6.2 dB gain antenna for transmission	Based on results of link budget analysis	Test
1.1.1.3	The surface spacecraft shall transmit on the 0.44 GHz frequency	Based on results of link budget analysis; necessary to match design specification of CubeSats	Test
1.1.1.4	The surface spacecraft shall use 1/2 rate turbo encoding for transmission	This is a low rate encoding scheme that is computationally inexpensive and provides a low necessary Eb/No	Test
1.1.1.5	The CubeSat shall be equipped with a minimum 6.2 dB gain antenna for transmission	Based on results of link budget analysis	Test
1.1.2	The CubeSat-to-Relay link shall provide at least 0.65 Mbps data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
1.1.2.1	The CubeSat shall be equipped with a 4 W RF UHF transmitter	Based on results of link budget analysis	Test
1.1.2.2	The CubeSat shall be equipped with a minimum 6.2 dB gain for transmission	Based on results of link budget analysis	Test
1.1.2.3	The CubeSat shall transmit on the 0.44 GHz frequency	Based on results of link budget analysis	Test
1.1.2.4	The CubeSat shall use 1/2 rate Turbo encoding for transmission	This is a low rate encoding scheme that is	Test

		computationally inexpensive and provides a low necessary Eb/No	
1.1.2.5	The Relay shall be equipped with a 5 by 0.34-meter parabolic dish antenna for reception	Based on results of link budget analysis	Test
1.1.3	The Relay-to-Earth link shall provide at least 2.93Tbit/sol data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
1.1.2.1	The Relay shall be equipped with a 50 W RF Ka-Band transmitter	Based on results of link budget analysis	Test
1.1.2.2	The Relay shall be equipped with a 6-meter parabolic dish antenna for transmission	Based on results of link budget analysis	Test
1.1.2.3	The Relay shall transmit on the 32.2 GHz frequency	Based on results of link budget analysis	Test
1.1.2.4	The Relay shall use 1/2 rate Turbo encoding for transmission	This is a low rate encoding scheme that is computationally inexpensive and provides a low necessary Eb/No	Test
1.1.2.5	The ground system shall use 34-m DSN stations for reception	Based on results of link budget analysis	Test
1.2	The ground system shall always provide a line of sight to Mars (except when occluded by the Sun)	LOS must be available from at least 1 ground station on Earth to Mars to make an Earth-Mars communications link and full availability of this link is required to meet Req 1	Analysis
2	The MC3 program shall provide at least 1 kbps uplink capability for spacecraft operating on the Martian surface	Stakeholder Requirement	Analysis
2.1	The CubeSat-to-Surface link shall provide at least 1 kbps data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
2.1.1	The CubeSat shall be equipped with a 4 W RF UHF transmitter	Based on results of link budget analysis	Test
2.1.2	The CubeSat shall be equipped with a quarter-wavelength monopole antenna for transmission	Based on results of link budget analysis	Test
2.1.3	The CubeSat shall transmit on the 0.44 GHz frequency	Based on results of link budget analysis	Test
2.1.4	The CubeSat shall use 1/2 rate Turbo encoding for transmission	This is a low rate encoding scheme that is computationally inexpensive and provides a low necessary Eb/No	Test
2.1.5	The surface spacecraft shall be equipped with a quarter-wavelength monopole antenna for reception	Based on results of link budget analysis	Test

2.2	The Relay-to-CubeSat link shall provide at least 1 kbps data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
2.2.1	The Relay shall be equipped with a 1 W RF UHF transmitter	Based on results of link budget analysis	Test
2.2.2	The Relay shall be equipped with a 5 by 0.34-meter parabolic dish antenna for transmission	Based on results of link budget analysis	Test
2.2.3	The Relay shall transmit on the 0.44 GHz frequency	Based on results of link budget analysis	Test
2.2.4	The Relay shall use 1/2 rate Turbo encoding for transmission	This is a low rate encoding scheme that is computationally inexpensive and provides a low necessary Eb/No	Test
2.2.5	The CubeSat shall be equipped with a quarter-wavelength monopole antenna for reception	Based on results of link budget analysis	Test
2.3	The Earth-to-Relay link shall provide at least 1 Tbit/sol data rate capability	Each link segment must meet the data rate requirement for the composite link	Analysis and test
2.3.1	The ground system shall be equipped with an 20000 W RF Ka-Band transmitter	DSN standard output power	Test
2.3.2	The ground system shall be equipped with a 34-meter parabolic dish antenna for transmission	Based on results of link budget analysis	Test
2.3.3	The ground system shall transmit on the 32.2 GHz frequency	Based on results of link budget analysis	Test
2.3.4	The ground system shall use 1/2 rate Turbo encoding for transmission	This is a low rate encoding scheme that is computationally inexpensive and provides a low necessary Eb/No	Test
2.3.5	The Relay shall be equipped with a 6-m parabolic dish antenna for reception	Based on results of link budget analysis	Test
2.4	The ground system shall always provide a line of sight to Mars (except when occluded by the Sun)	LOS must be available from at least 1 ground station on Earth to Mars to make an Earth-Mars communications link and full availability of this link is required to meet req 2	Analysis
3	The MC3 program shall provide 99% continuous coverage of the Martian surface	Stakeholder Requirement	Analysis
3.1	The MC3 constellation shall consist of CubeSats in 2 orbital planes offset by 90 degrees in RAAN	2 or more planes are necessary for complete coverage, this specific plane	Analysis

		count is derived from trade study	
3.2	Each orbital plane in the MC3 constellation shall contain 9 CubeSats	Derived from trade study	Analysis
3.3	Each CubeSat will be in a 4700 km radius circular orbit	Derived from trade study	Analysis
4	The MC3 program shall operate for a minimum of 10 years	Stakeholder Requirement	Analysis
4.1	Each CubeSat shall operate for a minimum of 35 months	This is the time between available transfer Earth-to-Mars transfer windows, including transit time	Analysis and test
4.2	Each CubeSat shall be replenished every 35 months until the completion of the mission	As CubeSats wear out, they will need replacement at this rate	Analysis
4.3	The Relay satellite shall operate for a minimum of 10 years	Due to the higher cost of the relay satellite, replenishment is not desirable	Analysis and test

Appendix B

SHAPED ANTENNA RELAY PARAMETERS

For the shaped antenna Relay configurations, there are a number of additional parameters calculated that are relevant to describing the performance of the constellation as a whole. These include the time of eclipse between CubeSats and a given Relay, the maximum time of eclipse between the Relay and the Earth, the orbital radius of the Relay, the antenna and beam shapes, and the synodic period of each plane-Relay pair. Each of these parameters varies for the different CubeSat orbital radii. These parameters are given in Tables 24 and 25 for the chosen UHF case for reference purposes.

Table 24: Shaped Antenna Relay Orbital Parameters

CubeSat Orbital Radius (km)	Relay Orbital Radius (km)	Synodic Period (hr)	CubeSat-Relay Eclipse (min)	Relay-Earth Eclipse (min)	Relay-Earth Eclipse (%)
3800	8097	2.95	60.0	138.9	37.2
3900	7301	3.41	62.4	115.0	36.0
4000	6741	3.98	64.8	99.2	35.0
4100	6322	4.69	67.2	87.9	34.1
4200	5996	5.62	69.7	79.5	33.4
4300	5733	6.87	72.2	72.9	32.8
4400	5517	8.66	74.7	67.7	32.3
4500	5336	11.43	77.3	63.4	31.8
4600	5182	16.28	79.9	59.9	31.3
4700	5086	24.66	82.2	57.7	31.1
5200	5705	24.66	83.8	72.2	32.7
5700	6347	24.66	85.6	88.5	34.2
6200	7014	24.66	87.6	106.8	35.5
6700	7709	24.66	89.6	127.0	36.6
7200	8436	24.66	91.4	149.5	37.7
7700	9197	24.66	93.2	174.4	38.6

Table 25: Shaped Antenna Relay Antenna Parameters

CubeSat Orbital Radius (km)	Antenna Cross-Track Size (m)	Antenna In-Track Size (m)	Antenna Cross-Track Viewing Angle (deg)	Antenna In-Track Viewing Angle (deg)
3800	5	0.34	60.0	9.54
3900	5	0.34	62.4	9.54
4000	5	0.34	64.8	9.54
4100	5	0.34	67.2	9.54
4200	5	0.34	69.7	9.54
4300	5	0.35	72.2	9.54
4400	5	0.35	74.7	9.54
4500	5	0.35	77.3	9.54
4600	5	0.35	79.9	9.54
4700	5	0.35	82.2	9.54
5200	5	0.36	83.8	9.54
5700	5	0.37	85.6	9.54
6200	5	0.38	87.6	9.54
6700	5	0.40	89.6	9.54
7200	5	0.41	91.4	9.54
7700	5	0.42	93.2	9.54

Appendix C

POSSIBLE CONFIGURATIONS FOR EACH LINK ELEMENT

For some link elements analyzed in Section 4.3, many possible hardware configurations were possible based on the power and antenna size ranges available for the given element. The data rate capabilities of these configurations are tabulated here for the purpose of identifying appropriate hardware configurations so that the data rate of each link element can be balanced. Configurations for both the uplink and downlink directions are identified. Only configurations using the selected frequency are given. For the transmit power of Earth-based ground stations, the given transmit power for the DSN 34-m stations is 43 dB-W [44]. These configurations are given in Tables 26-33

Table 26: Link 1 Downlink Configurations for UHF

Data Rate (Mbps)		CubeSat Transmit Power (W RF)
		10
CubeSat Radius (km)	3800	2.93
	3900	2.32
	4000	1.91
	4100	1.62
	4200	1.40
	4300	1.23
	4400	1.10
	4500	0.99
	4600	0.89
	4700	0.82
	5200	0.56
	5700	0.41
	6200	0.32
	6700	0.26
	7200	0.21
	7700	0.18

Table 27: Link 1 Uplink Configurations for UHF

Data Rate (Mbps)		CubeSat Transmit Power (W RF)									
		1	2	3	4	5	6	7	8	9	10
CubeSat Radius (km)	3800	0.29	0.59	0.88	1.17	1.46	1.76	2.05	2.34	2.63	2.93
	3900	0.23	0.46	0.70	0.93	1.16	1.39	1.62	1.86	2.09	2.32
	4000	0.19	0.38	0.57	0.77	0.96	1.15	1.34	1.53	1.72	1.91
	4100	0.16	0.32	0.49	0.65	0.81	0.97	1.14	1.30	1.46	1.62
	4200	0.14	0.28	0.42	0.56	0.70	0.84	0.98	1.12	1.26	1.40
	4300	0.12	0.25	0.37	0.49	0.62	0.74	0.86	0.99	1.11	1.23
	4400	0.11	0.22	0.33	0.44	0.55	0.66	0.77	0.88	0.99	1.10
	4500	0.10	0.20	0.30	0.39	0.49	0.59	0.69	0.79	0.89	0.99
	4600	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.71	0.80	0.89
	4700	0.08	0.16	0.24	0.33	0.41	0.49	0.57	0.65	0.73	0.82
	5200	0.06	0.11	0.17	0.22	0.28	0.33	0.39	0.44	0.50	0.56
	5700	0.04	0.08	0.12	0.16	0.21	0.25	0.29	0.33	0.37	0.41
	6200	0.03	0.06	0.10	0.13	0.16	0.19	0.22	0.26	0.29	0.32
	6700	0.03	0.05	0.08	0.10	0.13	0.16	0.18	0.21	0.23	0.26
	7200	0.02	0.04	0.06	0.09	0.11	0.13	0.15	0.17	0.19	0.21
	7700	0.02	0.04	0.05	0.07	0.09	0.11	0.13	0.14	0.16	0.18

Table 28: Link 2 Downlink Configurations for Ka-Band

Power (W RF)	1	2	3	4	5	6	7	8	9	10
Data Rate (kbps)	0.25	0.51	0.76	1.02	1.27	1.53	1.78	2.04	2.29	2.54

Table 29: Link 2 Uplink Configurations for Ka-Band

Transmit Power (W RF)	20000
Data Rate (Mbps)	5076.7

Table 30: Link 3 Downlink Configurations for UHF

Data Rate (Mbps)		Power (W RF)									
		1	2	3	4	5	6	7	8	9	10
CubeSat Radius (km)	3800	0.11	0.22	0.33	0.43	0.54	0.65	0.76	0.87	0.98	1.09
	3900	0.15	0.29	0.44	0.58	0.73	0.87	1.02	1.16	1.31	1.45
	4000	0.18	0.37	0.55	0.73	0.92	1.10	1.28	1.47	1.65	1.83
	4100	0.22	0.45	0.67	0.89	1.12	1.34	1.56	1.79	2.01	2.23
	4200	0.26	0.53	0.79	1.06	1.32	1.59	1.85	2.12	2.38	2.64
	4300	0.31	0.61	0.92	1.23	1.54	1.84	2.15	2.46	2.76	3.07
	4400	0.35	0.70	1.05	1.40	1.76	2.11	2.46	2.81	3.16	3.51
	4500	0.40	0.79	1.19	1.59	1.98	2.38	2.77	3.17	3.57	3.96
	4600	0.44	0.89	1.33	1.77	2.21	2.66	3.10	3.54	3.99	4.43
	4700	0.48	0.96	1.44	1.92	2.40	2.88	3.36	3.84	4.32	4.80
	5200	0.39	0.77	1.16	1.55	1.93	2.32	2.71	3.10	3.48	3.87
	5700	0.32	0.63	0.95	1.27	1.59	1.90	2.22	2.54	2.85	3.17
	6200	0.26	0.53	0.79	1.05	1.32	1.58	1.84	2.11	2.37	2.63
	6700	0.22	0.44	0.66	0.88	1.10	1.32	1.55	1.77	1.99	2.21
	7200	0.19	0.37	0.56	0.75	0.93	1.12	1.31	1.49	1.68	1.87
	7700	0.16	0.32	0.48	0.64	0.80	0.96	1.11	1.27	1.43	1.59

Table 31: Link 3 Uplink Configurations for UHF

Data Rate (Mbps)		Power (W RF)									
		1	2	3	4	5	6	7	8	9	10
CubeSat Radius (km)	3800	0.11	0.22	0.33	0.43	0.54	0.65	0.76	0.87	0.98	1.09
	3900	0.15	0.29	0.44	0.58	0.73	0.87	1.02	1.16	1.31	1.45
	4000	0.18	0.37	0.55	0.73	0.92	1.10	1.28	1.47	1.65	1.83
	4100	0.22	0.45	0.67	0.89	1.12	1.34	1.56	1.79	2.01	2.23
	4200	0.26	0.53	0.79	1.06	1.32	1.59	1.85	2.12	2.38	2.64
	4300	0.31	0.61	0.92	1.23	1.54	1.84	2.15	2.46	2.76	3.07
	4400	0.35	0.70	1.05	1.40	1.76	2.11	2.46	2.81	3.16	3.51
	4500	0.40	0.79	1.19	1.59	1.98	2.38	2.77	3.17	3.57	3.96
	4600	0.44	0.89	1.33	1.77	2.21	2.66	3.10	3.54	3.99	4.43
	4700	0.48	0.96	1.44	1.92	2.40	2.88	3.36	3.84	4.32	4.80
	5200	0.39	0.77	1.16	1.55	1.93	2.32	2.71	3.10	3.48	3.87
	5700	0.32	0.63	0.95	1.27	1.59	1.90	2.22	2.54	2.85	3.17
	6200	0.26	0.53	0.79	1.05	1.32	1.58	1.84	2.11	2.37	2.63
	6700	0.22	0.44	0.66	0.88	1.10	1.32	1.55	1.77	1.99	2.21
	7200	0.19	0.37	0.56	0.75	0.93	1.12	1.31	1.49	1.68	1.87
	7700	0.16	0.32	0.48	0.64	0.80	0.96	1.11	1.27	1.43	1.59

Table 32: Link 4 Downlink Configurations for Ka-Band

Data Rate (Mbps)		Power (W RF)										
		50	60	70	80	90	100	110	120	130	140	150
Dish Diameter (m)	2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.6
	4	0.8	1.0	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.3	2.4
	6	1.8	2.2	2.6	2.9	3.3	3.7	4.0	4.4	4.8	5.1	5.5
	8	3.3	3.9	4.6	5.2	5.9	6.5	7.2	7.8	8.5	9.1	9.8
	10	5.1	6.1	7.1	8.1	9.2	10.2	11.2	12.2	13.2	14.2	15.3
	12	7.3	8.8	10.3	11.7	13.2	14.7	16.1	17.6	19.1	20.5	22.0
	14	10.0	12.0	14.0	16.0	18.0	19.9	21.9	23.9	25.9	27.9	29.9
	16	13.0	15.6	18.2	20.8	23.4	26.1	28.7	31.3	33.9	36.5	39.1
	18	16.5	19.8	23.1	26.4	29.7	33.0	36.3	39.6	42.9	46.2	49.5
	20	20.4	24.4	28.5	32.6	36.6	40.7	44.8	48.9	52.9	57.0	61.1
	22	24.6	29.6	34.5	39.4	44.3	49.3	54.2	59.1	64.0	69.0	73.9

Table 33: Link 4 Uplink Configurations for Ka-Band

Data Rate (Mbps)		Power (W RF)
		20000
Dish Diameter (m)	2	81.2
	4	324.9
	6	731.0
	8	1299.6
	10	2030.7
	12	2924.2
	14	3980.1
	16	5198.5
	18	6579.4
	20	8122.7
	22	9828.5

Appendix D

COMPLETE ARCHITECTURE SELECTION SPREADSHEET

The architecture selection spreadsheet is the combined results of the coverage, stability, and link budget analyses. The constellation parameters orbital radius, number of planes, and number of satellites per plane are included in the left-most columns. The total number of satellites is calculated from these values. Each of the three link elements are evaluated as the maximum performance configuration identified for that link in Section 4.3. The total data rates for the three links are taken as the sum of all elements within the link operating simultaneously at full capacity. If outage times are to be accounted for, this should be done in this column. The total data rate of the system is calculated as the maximum value of the three total link data rates. This spreadsheet is given in Figure 32.

Radius	# of planes	# of sat per plane	Total Satellites	Surface Link Mbps	Cube Relay Link Mbps	Relay Earth Link Mbps	Total Surface Link Mbps	Total C-R Link Mbps
4000	3	15	45	1.91	1.83	74.00	85.95	82.52
4100	3	11	33	1.62	2.23	74.00	53.46	73.65
4200	3	10	30	1.40	2.64	74.00	42.00	79.35
4300	3	7	21	1.23	3.07	74.00	25.83	64.50
4400	3	7	21	1.10	3.51	74.00	23.10	73.74
4500	3	7	21	0.99	3.96	74.00	20.79	83.23
4600	3	6	18	0.89	4.43	74.00	16.02	79.70
4700	3	5	15	0.82	4.80	74.00	12.30	71.99
3800	4	12	48	2.93	1.09	74.00	140.64	52.20
3900	4	10	40	2.32	1.45	74.00	92.80	58.07
4000	4	8	32	1.91	1.83	74.00	61.12	58.68
4100	4	7	28	1.62	2.23	74.00	45.36	62.49
4200	4	7	28	1.40	2.64	74.00	39.20	74.06
4300	4	6	24	1.23	3.07	74.00	29.52	73.72
4400	4	6	24	1.10	3.51	74.00	26.40	84.27
4500	4	6	24	0.99	3.96	74.00	23.76	95.12
4600	4	5	20	0.89	4.43	74.00	17.80	88.56
4700	4	5	20	0.82	4.80	74.00	16.40	95.99
3800	5	9	45	2.93	1.09	74.00	131.85	48.94
3900	5	8	40	2.32	1.45	74.00	92.80	58.07
4000	5	7	35	1.91	1.83	74.00	66.85	64.18
4100	5	6	30	1.62	2.23	74.00	48.60	66.96
4200	5	6	30	1.40	2.64	74.00	42.00	79.35
4300	5	6	30	1.23	3.07	74.00	36.90	92.15
4400	5	5	25	1.10	3.51	74.00	27.50	87.78
4500	5	5	25	0.99	3.96	74.00	24.75	99.09
4600	5	5	25	0.89	4.43	74.00	22.25	110.70
4700	5	5	25	0.82	4.80	74.00	20.50	119.98
4700	2	9	18	0.82	4.80	74.00	14.76	86.39
5200	2	8	16	0.56	3.87	74.00	8.96	61.91
5700	2	6	12	0.41	3.17	74.00	4.92	38.04
6200	2	5	10	0.32	2.63	74.00	3.20	26.31
6700	2	5	10	0.26	2.21	74.00	2.60	22.07
7200	2	4	8	0.21	1.87	74.00	1.68	14.94
7700	2	4	8	0.18	1.59	74.00	1.44	12.74
5200	3	5	15	0.56	3.87	74.00	8.40	58.04
5700	3	4	12	0.41	3.17	74.00	4.92	38.04
6200	3	4	12	0.32	2.63	74.00	3.84	31.58
6700	3	4	12	0.26	2.21	74.00	3.12	26.49
7200	3	3	9	0.21	1.87	74.00	1.89	16.81
7700	3	3	9	0.18	1.59	74.00	1.62	14.33
5200	4	4	16	0.56	3.87	74.00	8.96	61.91
5700	4	4	16	0.41	3.17	74.00	6.56	50.72
6200	4	4	16	0.32	2.63	74.00	5.12	42.10
6700	4	4	16	0.26	2.21	74.00	4.16	35.32
7200	4	4	16	0.21	1.87	74.00	3.36	29.89
7700	4	3	12	0.18	1.59	74.00	2.16	19.11

Figure 32: Architecture Selection Spreadsheet

Appendix E

DOUBLE SATELLITE COVERAGE RESULTS

Double satellite coverage is defined as two CubeSats having simultaneous LOS access to the entire coverage area at all times. As it was computationally inexpensive to calculate these results in addition to the single satellite coverage results, they are included here in Figures 33 and 34.

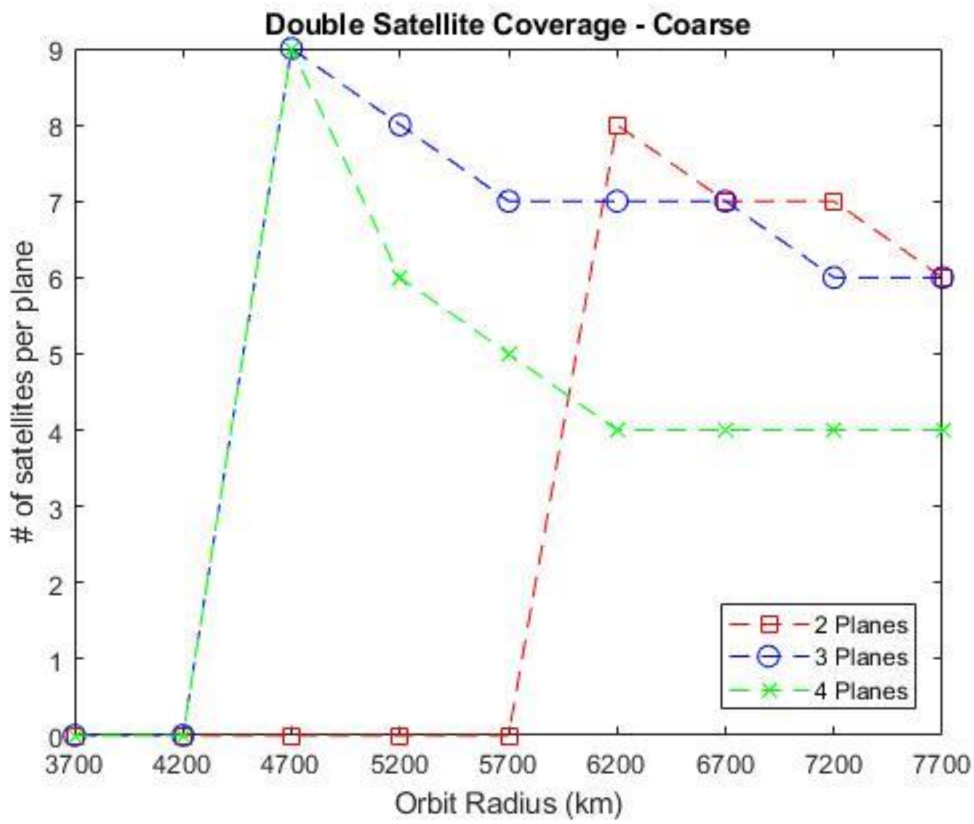

Figure 33: Double Satellite Coverage Coarse Results

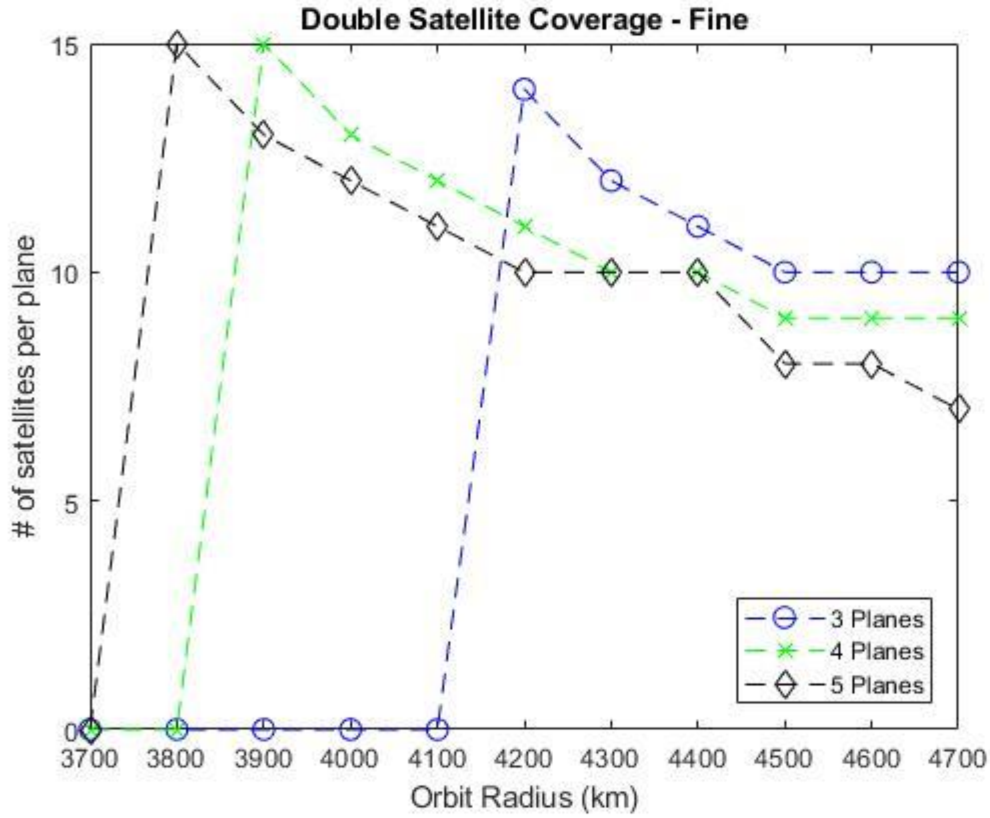

Figure 34: Double Satellite Coverage Fine Results